

**Charles University in Prague**

Faculty of Social Sciences  
Institute of Economic Studies



DISSERTATION

**Three Essays on Electricity Markets**

Author: **PhDr. Petra Luňáčková**

Supervisor: **prof. Ing. Karel Janda M.A., Dr., Ph.D.**

Academic Year: **2017/2018**

## **Declaration of Authorship**

The author hereby declares that she compiled this thesis independently, using only the listed resources and literature, and the thesis has not been used to obtain a different or the same degree.

The author grants to Charles University permission to reproduce and to distribute copies of this thesis document in whole or in part.

Prague, December 19, 2017

---

Signature

## **Acknowledgments**

I am about to finish my PhD studies which makes me look back. Studying was an inherent part of my life for many years, I have learned a lot and knowledge I have gained is not limited to academia. I value experience and perspective IES FSV UK education gave me.

I would like to express my gratitude to my supervisor prof. Karel Janda for his guidance and help and to my colleague Ladislav Křištofuk for many useful insights and discussions and also for making me believe “I can do it”. I also thank my friends for listening to me.

I am grateful to my sisters and parents for their support and understanding. Last but not least, my thanks go to Jirka, because love makes wishes easier to reach.

This thesis is part of a project that has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 681228.

## Abstract

This thesis consists of three papers that share the main theme - energy. The articles introduce characteristics and behavior of electricity focusing on its unique properties. The dissertation aims at the Czech electricity market and analyzes also highly discussed solar power plants.

The first article studies long term memory properties of electricity spot prices through the detrended fluctuation analysis, as electricity prices are dominated by cycles. We conclude that Czech electricity prices are strongly mean reverting yet non-stationary.

The second part of the dissertation investigates possible asymmetry in the gas - oil prices adjustment. Oil prices determine the price of electricity during the times of peak demand, as the reaction of power plants fueled by oil is quick but marginal costs are high. We chose the gasoline - crude oil relationship known as “rockets and feathers” effect and offer two new tests to analyze such type of relationship as we believe that error correction model is not the most suitable tool. Analyzing international dataset we do not find statistically significant asymmetry.

The third study assesses the impact of renewable energy sources, solar plants in particular, on the electricity spot prices, its goal is to verify the merit order effect on Czech market data. We describe history and consequences of photovoltaic power plants boom in the Czech Republic. With the use of the instrumental variables method we show that merit order effect differs for various renewable sources. Czech solar plants cause no merit order effect which is in contradiction to the preferential treatment they enjoy. The merit order effect of other renewables is present, however, if compared to subsidies, it is not of substantial magnitude.

**JEL Classification** Q40, Q28, C13

**Keywords** electricity, merit order effect, market price behaviour

**Author's e-mail** lunackova.petra@gmail.com

**Supervisor's e-mail** Karel-Janda@seznam.cz

## Abstrakt

Tuto disertaci tvoří tři články propojené společným ústředním tématem - elektřinou. Všechny kapitoly se soustředí na vlastnosti cen elektřiny a popisují jejich chování a jedinečné rysy. Disertace je zaměřena na elektřinu v českých podmínkách a věnuje se také, u nás velmi rozšířeným, solárním elektrárnám.

První článek zkoumá přítomnost dlouhé paměti na cenách elektřiny obchodované na českém denním spotovém trhu s využitím metody DFA, která se hodí pro časové řady s cyklickým chováním. Analyzované ceny mají tendenci se vracet ke své střední hodnotě ale přitom jsou nestacionární.

Druhý článek se věnuje asymetrickému přizpůsobování cen, analyzuje chování a vzájemné přizpůsobování cen ropy a benzínu známe pod označením “rockets & feathers”. V očích veřejnosti roste cena benzínu rychlejším tempem než klesá v porovnání s poklesem ceny ropy. Domníváme se, že error correction model, který se v těchto případech běžně používá, není nejvhodnější, a proto navrhuje nový přístup k testování asymetrie. Námi navržené testy asymetrické přizpůsobování cen ropy a benzínu neukazují.

Třetí článek je zaměřen na dopad obnovitelných zdrojů, zejména solárních elektráren, na ceny elektřiny. Cílem je ověřit existenci merit order efektu na českých datech. Úvodní část této kapitoly představuje příběh solárního boomu v České republice a jeho důsledky. S použitím metody instrumentálních proměnných se ukazuje, že merit order efekt se pro různé obnovitelné zdroje liší. České solární elektrárny merit order efekt nepřinášejí, což je v přímém kontrastu s jejich štědrá finanční podporou. Ostatní české obnovitelné zdroje merit order efekt způsobují, nicméně v porovnání s dotacemi není jeho vliv finančně dostatečně významný.

# Contents

List of Tables	viii
List of Figures	ix
Acronyms	x
<b>1 General Introduction</b>	<b>1</b>
<b>2 Long-term memory in electricity prices: Czech market evidence</b>	<b>6</b>
2.1 Introduction . . . . .	7
2.2 Brief literature review . . . . .	9
2.3 Methodology . . . . .	11
2.3.1 Long-term memory . . . . .	11
2.3.2 Detrended fluctuation analysis . . . . .	12
2.3.3 Useful properties of MF-DFA . . . . .	14
2.3.4 Alternative estimators . . . . .	15
2.4 Data description . . . . .	16
2.5 Results and discussion . . . . .	20
2.6 Conclusion . . . . .	26
<b>3 Rockets and feathers meet Joseph: Reinvestigating the oil-gasoline asymmetry on the international markets</b>	<b>28</b>
3.1 Introduction . . . . .	29
3.2 Literature review . . . . .	30
3.3 Data and preliminary analysis . . . . .	33
3.4 Methodology . . . . .	37
3.4.1 Wave test . . . . .	38
3.4.2 Rescaled range ratio test . . . . .	39
3.4.3 Statistical testing procedure . . . . .	40

---

3.5	Application and discussion . . . . .	42
3.6	Conclusion . . . . .	43
<b>4</b>	<b>The Merit Order Effect of Czech Photovoltaic Plants</b>	<b>50</b>
4.1	Introduction . . . . .	51
4.2	Czech Energy Market and Renewable Sources Policies . . . . .	54
	4.2.1 Market Design . . . . .	54
	4.2.2 Renewable Sources Policies . . . . .	57
4.3	Literature Review . . . . .	61
4.4	Data . . . . .	64
4.5	Methodology . . . . .	67
4.6	Results . . . . .	69
4.7	Discussion . . . . .	74
4.8	Conclusions and Policy Implications . . . . .	76
	<b>Bibliography</b>	<b>91</b>
<b>A</b>	<b>Response to Opponents' Reports on Dissertation Thesis</b>	<b>I</b>

# List of Tables

2.1	Descriptive statistics . . . . .	17
3.1	Summary of the “rockets and feathers” literature . . . . .	46
3.2	Unit-root and stationarity testing . . . . .	47
3.3	Cointegration & error-correction term testing . . . . .	48
3.4	Asymmetry in error-correction term testing . . . . .	49
4.1	Czech Electricity Production, Consumption and Export 2010-2015	58
4.2	Czech 2015 Electricity Production and Installed Capacity . . . .	59
4.3	Czech RES Financing 2009-2015 . . . . .	60
4.4	Czech Solar Feed-in Tariffs 2005-2014, in CZK . . . . .	61
4.5	Production of Czech power plants 2001-2015, in GWh . . . . .	62
4.6	Summary of utilized variables, in MWh, 50 371 observations . .	65
4.7	Share of photovoltaics in renewables and total consumption 2006 - 2015, in MWh . . . . .	66
4.8	Results of IV Regression, hourly data . . . . .	70
4.9	Results of IV Regression, daily data . . . . .	72
4.10	Results of IV Regression, weekly data . . . . .	73
A.1	Overview of the Contribution of Petra Lunackova . . . . .	IV



# List of Figures

2.1	Time series plots . . . . .	18
2.2	Histograms of electricity prices and changes in prices . . . . .	19
2.3	Correlation structure of prices . . . . .	20
2.4	Cyclical properties of electricity prices and volumes . . . . .	21
2.5	GPH estimates of Hurst exponent . . . . .	22
2.6	Scaling of fluctuations $F(s)$ . . . . .	24
2.7	Scaling of fluctuations $F(s)$ for separate years . . . . .	25
3.1	Crude oil and gasoline prices . . . . .	45
3.2	Error-correction terms . . . . .	45
4.1	Merit order effect mechanism (illustrative scheme) . . . . .	52
4.2	Shares of volumes produced (in blue) and shares of support paid (in red) by type of RES and secondary sources, Czech Republic, 2013 . . . . .	54
4.3	Czech Electricity Power Balance, 2015 . . . . .	59
4.4	Power Balance - Resulting Possible Trade Opportunity, 2015 . .	60
4.5	Production Profile Example, Czech Republic, April 17th, 2014 .	71

# Acronyms

<b>ADF</b>	Augmented Dickey-Fuller test
<b>APX</b>	Amsterdam Power Exchange
<b>ARFIMA</b>	fractionally integrated autoregressive moving average
<b>CEPS</b>	Czech Electricity Transmission System
<b>CHMI</b>	Czech Hydrometeorological Institute
<b>CO</b>	crude oil
<b>CSP</b>	concentrating solar power
<b>CTK</b>	Czech News Agency
<b>CZK</b>	Czech crown
<b>DFA</b>	detrended fluctuation analysis
<b>DW</b>	Durbin-Watson test
<b>ECM</b>	error correction model
<b>EEX</b>	European Energy Exchange
<b>ERU</b>	Energy Regulatory Office
<b>EU</b>	European Union
<b>FIFO</b>	first in first out
<b>GARCH</b>	generalized autoregressive conditional heteroskedasticity
<b>GDP</b>	gross domestic product
<b>GPH</b>	Geweke & Porter-Hudak estimator
<b>GWh</b>	gigawatt-hour
<b>H</b>	Hurst exponent
<b>HAR-RV</b>	heterogenous autoregressive model with realized variance
<b>IES FSV UK</b>	Institute of Economic Studies, Faculty of Social Sciences, Charles University

---

<b>KPSS</b>	Kwiatkowski–Phillips–Schmidt–Shin test
<b>MF-DFA</b>	multifractal detrended fluctuation analysis
<b>MOE</b>	merit order effect
<b>MW</b>	megawatt
<b>MWh</b>	megawatt-hour
<b>OLS</b>	ordinary least squares
<b>OTE</b>	Czech Electricity and Gas Market Operator
<b>RES</b>	renewable energy sources
<b>RRR</b>	rescaled range ratio
<b>SRMC</b>	short run marginal costs
<b>TAAF</b>	Theiler’s Amplitude Adjusted Fourier Transform
<b>WTI</b>	West Texas Intermediate

# Chapter 1

## General Introduction

Energy is a phenomenon powering our society and that is why I have devoted my dissertation to electricity. This work consists of three essays which share the main theme - electricity. The research is dedicated to electricity characteristics and dynamics, and focuses on the Czech electricity market analyzing also the highly discussed photovoltaic power plants. All three papers discuss policy implications of respective results.

The first paper “Long-term memory in electricity prices: Czech market evidence” was published in 2013 in the Czech Journal of Economics and Finance 63(5). It is a natural starting point of this dissertation as at the beginning we were interested in electricity prices as such and thus our first analysis focuses on electricity spot prices properties, in particular on their long term memory.

Long-term memory is defined in Chapter 2.3.1, even though it is called “long”, which we often (together with memory) associate with time, it is not defined in terms of units of time. Instead, it is defined by the specific decay of auto-correlation function. There is specific vanishing pattern rather than time.

Electricity is a flow commodity, characterized by strong daily and weekly cycles and heavily dependent on season, moreover it reflects weather and temperature changes in real time. As a consequence electricity prices are highly volatile, including spikes. We performed detrended fluctuation analysis which enabled us to separate cyclical properties from the long-term memory.

Our results show that Czech electricity spot prices time series is non-stationary, strongly persistent but at the same time it remains mean reverting. These characteristics are stable across time and can be found also in foreign spot time series. Thus, we conclude that Czech electricity market, despite being rather young, is comparable to its older siblings in the western EU countries.

It has reached European level also in terms of structure, liquidity and cross border integration. As to our knowledge in 2013 there was not published any other study focused on the properties of Czech electricity spot prices.

The second paper is devoted to the gas and oil prices, which usually determine the price of electricity during the peak times, as the reaction of power plants using these types of fuels is quick but marginal costs are high. This analysis was published in *Energy Economics* 49 in year 2015 under the name “Rockets and feathers meet Joseph: Reinvestigating the oil-gasoline asymmetry on the international markets” referring to the popular belief that oil prices rise at rocket pace but fall slowly like feathers.

We return again to the property of persistence (personified by Joseph) and we analyze weekly gasoline prices for 6 EU countries and USA. Price movements of oil and gasoline are usually studied based on their cointegration. Both commodities are caught in long term equilibrium relationship which is often proved through some type of error correction model (ECM). Given the way the error correction model is built it assumes return to the equilibrium to be fairly rapid. However, we show that gasoline prices return to their equilibrium quite slowly. Moreover, we claim this dynamics on Joseph effect (long periods of above and below equilibrium) rather than on the error correction term. We argue that due to the strong memory of the time series, error correction models are not suitable for analysis of the relationship between oil and gasoline prices. Our idea is based on the fact that error correction terms are not integrated of order zero which is significant for the appropriateness of the ECM. Also literature reports problems with the ECM approach (Alogoskoufis & Smith 1991; Grant & Lebo 2016).

We introduce new tests based on the mean reversion. We call the first one “wave test”, it works with the positive and negative error correction terms  $\hat{\epsilon}_t$  as for the symmetry their expected average is zero. Contrary to “rockets and feathers” asymmetry where one would expect the positive error correction terms to prevail.

The second test is called “rescaled range ratio” and is based on the idea of testing for difference in fractional integration parameters of the positive and negative part of the error correction term and put in practice by measuring the mean-reversion speed of positive and negative part of the error correction term.

Performing these tests of the asymmetric price adjustment we conclude that there is no statistically significant asymmetry. The proposed tests are

not limited to the particular relationship and can be used for asymmetric price adjustment analysis in general.

The third paper named “The Merit Order Effect of Czech Photovoltaic Plants” was recently published in Energy Policy 106 (2017) and turns attention to the green side of the electricity, analyzing the merit order effect (MOE), in particular the MOE of solar power plants. Preliminary version of the paper was presented at the 9th Biennial Conference of the Czech Economic Society in 2016.

Electricity prices have always been weather dependent but renewable energy support policy imposed the weather dependence also on the supply side of the electricity market which makes their analysis further more complex.

Merit order effect reflects short run marginal costs of renewable energy sources (RES) which are basically zero and RES preferential treatment endorsed by green governmental policy. In plain words, MOE, typically negative, assumes that green electricity sold in the wholesale market drives down electricity spot price, thus brings some savings which counterbalance the total spending on green subsidies.

Our analysis aims to quantify the merit order effect using Czech market data. We describe the unprecedented rise of photovoltaic power plants in the Czech Republic, related policies and its consequences. The study analyzes electricity spot market prices with the focus on electricity source throughout five years period from 2010 to 2015.

We estimate the MOE as elasticity of electricity spot price with respect to the change in supply of electricity from the renewable sources. As solar energy forms significant part of the renewable energy sources we estimate the MOE separately for solar and other renewables. Our model is based on the instrumental variables method and corrects for typical (statistically unfriendly) electricity prices time series features.

We find no MOE for solar plants and small MOE for other renewable sources, incomparable to subsidies. Our results suggest that the MOE effect does not have to hold for every type of renewable energy sources which could help the green policy to find its direction as sources that bring some savings make more economic sense. Such a finding is quite novel in this field and contributes to the analysis of RES impact in general. Our conclusion that MOE is not automatic is supported also by minor part of the literature, see e.g. Nelson *et al.* (2012) or Milstein & Tishler (2011). No solar MOE becomes even more important in the light of enormous support it enjoys.

Actually, the results show that Czech solar production does not drive the marginal plant out of the market, the non-decrease of electricity wholesale price is a consequence. The point is hidden in the low productivity of Czech solar power plants, not in the overall number of them. The explanation of the Czech non-negative solar MOE stands on three reasons - political, geographical and productivity. Czech geographical conditions do not favor solar power plants, actual production falls behind installed capacity and is marginal compared to the overall production. Last but not least, political will to support RES allowed solar development that market would have never made possible (under the then conditions).

At the first sight, energy markets may seem already reformed, the liberalization process was more or less successful, however, the second sight suggests there is a lot head of us. Existing markets face challenges in terms of intermittent sources accommodation, supply securing, and far in the future there is the dream of single European internal energy market. Reforms both undertaken and planned must support the competitiveness of European production. The pressure on current infrastructure and efficiency requires either reform or evolution towards new market design. In the light of these crucial issues deeper understanding of all aspects related to the electricity behavior and markets is of great importance.

The objective of this dissertation is to contribute to the energy economics knowledge and understanding of the electricity market behavior by above written results. Each chapter brings policy implications. The first article points out that Czech electricity market has undergone an evolution and that electricity prices are partially predictable due to their mean-reversion, which also suggests that shocks are generally rather short-lived. Message of the “rockets and feathers” paper is straightforward, given that we have found no statistically significant asymmetry with regard to price adjustment, we suggest policy makers do not interfere. We did not identify any market failure, hence we believe there is no need for interventions. The impact of the MOE paper is broader, it suggests that the Czech solar preference might be reconsidered, moreover, it underlines the extend to which a policy can (unintentionally) change the market.

Results of the dissertation offer several open questions that a follow-up research could answer. The first paper focused on the spot prices properties could be extended to include also volatility analysis. The non-negative MOE of Czech solar plants deserves verification, methodologically different approach

should be applied in order to confirm the findings. Further, meta-analysis of the existing MOE literature could also shed more light on this issue. Stability of the results across time should be also checked, splitting the dataset into subsamples, one for each year, would show whether the MOE holds for each year.



## Chapter 2

# Long-term memory in electricity prices: Czech market evidence

**Published as:** Křišťoufek, Ladislav and Luňáčková, Petra (2013): “Long-term memory in electricity prices: Czech market evidence.” *Finance a úvěr - Czech Journal of Economics and Finance* 63(5): pp. 407-424.

**Abstract:** We analyze long-term memory properties of hourly prices of electricity in the Czech Republic between 2009 and 2012. Various statistical properties of the electricity prices are studied and as the dynamics of the electricity prices is dominated by cycles – mainly intraday and daily – we opt for the detrended fluctuation analysis, which is well suited for such specific series. We find that the electricity prices are non-stationary but strongly mean-reverting which distinguishes them from other financial assets which are usually characterized as unit root series. Such description is attributed to specific features of electricity prices, mainly to non-storability. Additionally, we argue that the rapid mean-reversion is due to the principles of electricity spot prices. These properties are shown to be stable across all studied years.

Keyword: electricity, Hurst exponent, persistence, cycles

*JEL codes: C13, C22, L94*

## 2.1 Introduction

Electricity is a flow commodity with unique characteristics that influence the way it is traded and thus the behavior of spot and futures prices in the market. Electricity cannot be effectively stored (with minor exception of pumped-storage hydro power plants that are scarce) so that the adjustment of demand and supply must be instantaneous. Demand for electricity reflects human behavior and temporal patterns of human life with daily and weekly routines which is reflected in the daily pattern with single or double peak structure and weekly patterns (Simonsen *et al.* 2004). On higher scales, the seasonal fluctuations are mainly caused by weather, in particular temperature and number of hours of daylight (Lucia & Schwartz 2002). The seasonal patterns are strongly geographically dependent – in northern countries, the highest consumption is usually observed during winter months due to heating, and in southern countries, air-conditioning increases the consumption during summer (Zachmann 2008).

Electricity prices on the spot market are very sensitive to temperatures and especially to sudden unexpected weather changes, which are expected up to a certain point. The weather forecast is never perfect which causes the spot prices to be much more volatile than other financial assets (Asbury 1975). Moreover, electricity supply side is also weather dependent, which is evidently more valid for the renewable sources of energy such as wind turbines and photovoltaic power plants (Von Bremen 2010).

Demand for electricity is highly inelastic. In short run, it is absolutely inelastic so that the price is determined by the supply curve (merit order curve, marginal cost curve) completely. The curve resembles upward sloping stairway, each step approximately represents a different type of a power plant and thus a different level of marginal costs. The price on the market rises until it reaches the marginal costs for a MWh of the power plant of the next level, after that the supply rises. This is why the merit order curve is not smooth. In order to produce an additional MWh, more expensive power sources (plants) are activated and as the supply is increasing, the price increases as well (Geman & Roncoroni 2006; Sensfuss *et al.* 2008).

High (or excess) volatility is another typical feature of electricity prices and it is mainly due to the non-storability of electricity itself. There are no reserves that could be used in case of sudden increase in demand or weather change (Janczura *et al.* 2013). The prices are not only volatile, the volatility has also a

tendency to cluster. Apart from the clustering, volatility is also characteristic by an inverse leverage effect – positive shocks increase price volatility more than the negative ones (Knittel & Roberts 2005). In addition, the electricity prices tend to “jump” very frequently. These jumps are usually referred to as “spikes” and these are typical by a sharp increase followed by a slower decrease causing pronounced asymmetry. Due to the properties described above, the electricity prices are often treated as non-stationary.

Unlike other financial time series, specifically prices of various assets, the electricity prices are mean reverting (Simonsen 2003; Weron & Przybyłowicz 2000). According to Barlow (2002), estimates of time for mean reversion are from two to six days. Geman (2005) states that with constant or slightly increasing demand, supply side is able to adjust the pattern so that the prices remain close to their mean value. However, the strength of mean reversion varies from study to study – some studies report electricity prices to be stationary (Park *et al.* 2006), other find weak mean reversion close to the unit root (Simonsen 2003) with many results laying in between. More detailed description of these results is provided in the Brief literature review section.

The electricity prices are also influenced by factors that are unthinkable for other “typical” financial assets – technical constraints. Power plant which is out of order due to either technical problems or regular maintenance can influence the price because the number of power plants is small and limited. Electricity can be easily and quickly transported but transmission lines have capacity constraints which must not be exceeded. That is the main reason why electricity prices differ in neighboring areas but it can also cause high levels of volatility due to potential instability of the whole system (Borenstein *et al.* 1997a).

Last but not least, the electricity demand and thus also the prices depend on business cycle, economic activity or growth. Electricity consumption and economic growth are bounded; different studies suggest different direction of the causality, from electricity consumption to GDP, vice versa or both (Soytas & Sari 2003; Lee 2005; Squalli 2007; Ciarreta & Zarraga 2010).

In our study, we focus on various properties of the electricity prices in the Czech Republic with a special attention put on long-term memory of the spot prices. To our best knowledge, this is the first such study of the Czech electricity market. The market has been fully deregulated since 2006 and the network of power plants consists of the less expensive hydro and nuclear power plants, the more expensive hard coal and gas power plants, with lignite plants somewhere

in between (Sensfuss *et al.* 2008). Small increase in demand can thus put into function considerably more expensive power plants and the occurrence of spikes is potentially high.

OTE (Czech electricity and gas market operator, established in 2001) organizes the day-ahead spot electricity market since 2002. It has been coupled through implicit auctions (meaning electricity and capacity are traded together up to the available cross border capacity) with the organized day-ahead electricity market in the Slovak Republic since 2009, with the day-ahead electricity market in Hungary since 2012 and with Romania since 2014. This mechanism is known as market coupling and it is a precondition for European electricity market integration. Czech day-ahead spot electricity market has a form of a daily auction, a traded period is 1 hour, a minimum tradable volume is 1 MWh and the trading currency is EUR. The market closes always the day before at 11AM. Volume of electricity registered in the OTE system for day-ahead market was 10,971 GWh for sale and 10,562 GWh for purchase in 2012<sup>1</sup>.

In the paper, we describe temporal patterns, distributional properties and mainly the correlation structure with a special attention on long-term memory of the prices. To do so, we utilize the detrended fluctuation analysis, which is well suited for time series with such a complicated structure as the electricity spot prices. We show that the prices are non-stationary, strongly persistent but they remain strongly mean reverting which well distinguishes them from other financial prices such as stocks and exchange rates which follow random walk pattern (Cont 2001). To our best knowledge, this the first detailed analysis of the Czech electricity prices and their dynamics. The paper is structured as follows. Section 2 focuses on recent studies on long-term memory properties of electricity prices to which we mostly contribute. Section 3 presents the data, subsequent Section 4 describes the methodology. Section 5 discusses the results and Section 6 concludes.

## 2.2 Brief literature review

Correlations and memory characteristics of electricity prices have been a frequent object of interest of many studies in recent years. Weron & Przybyłowicz (2000) analyze California Power Exchange (CalPX) and Swiss Electricity hourly prices using the rescaled range analysis finding mean-reverting characteristics.

---

<sup>1</sup>Details are available at <https://www.ote-cr.cz/statistics>.

The analysis is then broadened by Weron (2002) who studies four electricity markets (CalPX, Nord Pool, Entergy and UK spot) with three different methods (rescaled range analysis, detrended fluctuation analysis and periodogram methods) and confirms that returns of the electricity prices are anti-persistent. Simonsen (2003) analyzes the Nord Pool prices using multi-scale wavelet approach and compares it with the standard rescaled range analysis to show that the returns of electricity prices are weakly anti-persistent. The author stresses that a choice of an appropriate technique for the long-term memory estimation is crucial. Park *et al.* (2006) examine 11 US electricity markets using the vector autoregression methodology but importantly finds several price series to be stationary which is well against a standard understanding of prices of financial assets which are typically a unit root series and thus strongly non-stationary.

Koopman *et al.* (2007) develop an adjusted fractionally integrated autoregressive moving average model with generalized autoregressive conditional heteroskedasticity (ARFIMA-GARCH), which is able to capture day-of-the-week patterns and extreme price movements, specifically for the electricity prices and on three European markets (German EEX, French Powernext and Dutch APX), they show that the weekly patterns are indeed crucial in the daily prices analysis. Norouzzadeh *et al.* (2007) study long-term memory and multifractality of the Spanish spot market finding persistent yet strongly mean-reverting prices. Erzgraber *et al.* (2008) focus on long-term memory in Nord Pool markets and find the returns to be weakly (compared to the previous study) anti-persistent. They also find that the strength of memory depends on the daytime of the measurement, i.e. the prices are not only correlated from hour to hour but also in the same hour from day to day. Moreover, they show that the memory parameter varies strongly in time. Uritskaya & Serletis (2008) examine the electricity prices of Alberta and Mid-C electricity prices using the detrended fluctuation analysis and spectral exponents finding that both the Alberta and Mid-C prices are persistent and mean-reverting. However, the former remains stationary whereas the latter does not.

Malo (2009) combines various properties of electricity prices and utilizes Markov-switching multifractal model with conditional copulas to construct a model for risk minimization of the Nord Pool markets. Comparing various methods of long-term memory estimation, the author finds anti-persistent returns of electricity prices. Utilizing various copula specifications, conditional value at risk is also discussed in detail.

Alvarez-Ramirez & Escarela-Perez (2010) analyze Ontario and Alberta electricity markets with the detrended fluctuation analysis and the Allan factor model to show that the long-term memory properties of both prices and demand strongly vary in time. Haugom *et al.* (2011) model Nord Pool electricity prices using long-term memory mimicking heterogenous autoregressive model with realized variance (HAR-RV) and show that incorporating the strongly persistent realized variance improves the predicting power of the model. And Rypdal & Lovsleten (2013) model the Nord Pool data using the Multifractal random walk model adjusted for mean-reversion and volatility persistence to capture the most important characteristics of the electricity prices. Using the model, the authors show that the electricity prices characteristics are very different from the ones of the stock market prices. In our analysis, we apply the detrended fluctuation analysis on hourly spot prices of the Czech electricity. Specifically, we utilize its ability to separate cycles and seasonalities from the long-term memory.

## 2.3 Methodology

### 2.3.1 Long-term memory

Long-term memory evokes the notion of time, however, it is not defined in terms of units of time. Instead, it is defined by the specific decay of auto-correlation function, regardless the time dimension of the series. There is specific vanishing pattern rather than time. Long-term memory is traditionally connected to slowly decaying auto-correlation functions. For the auto-correlation function  $\rho(k)$  with a lag  $k$ , the decay is described as asymptotically hyperbolic so that  $\rho(k) \propto k^{2H-2}$  where  $k \rightarrow +\infty$ . The auto-correlation function thus follows an asymptotic power law. A characteristic parameter of the long-term memory is the Hurst exponent  $H$  which ranges between 0 and 1 for stationary processes. The breaking value of 0.5 is connected to a short-term correlated process (usually characteristic by exponential or more rapid decay of the auto-correlation function). For  $H > 0.5$ , the underlying process is positively correlated and locally trending, and it is traditionally labeled as a persistent process. For  $H < 0.5$ , the process is anti-persistent and it switches its direction more frequently than a random process would (Beran 1994; Samorodnitsky 2006).

For non-stationary processes, the definition of long-term memory via the auto-correlation function suffers as the process has infinite variance and the

correlations do not exist. For this matter, but also in a general case, a spectrum-based definition is used. Assuming that the spectrum or pseudo-spectrum of an underlying process exists near to the origin, i.e.  $f(\lambda)$  exists for  $\lambda \rightarrow 0+$ , we define long-term memory via a power-law at origin of the spectrum, i.e.  $f(\lambda) \propto \lambda^{1-2H}$  for  $\lambda \rightarrow 0+$ . For persistent processes,  $f(\lambda)$  diverges at the origin whereas for the anti-persistent processes, it collapses to zero (Samorodnitsky 2006).

Historically, there have been two major streams of the Hurst exponent estimators – time domain estimators and frequency domain estimators. The time domain estimators are based on the auto-correlation definition of long-term memory and its implications to a scaling of variance of partial sums. To name the most frequently used ones, we have rescaled range analysis (Hurst 1951; Mandelbrot & Wallis 1968; Mandelbrot & van Ness 1968), detrended fluctuation analysis (Peng *et al.* 1993; 1994; Kantelhardt *et al.* 2002), generalized Hurst exponent approach (Alvarez-Ramirez *et al.* 2002; Di Matteo *et al.* 2003; Di Matteo 2007) and detrending moving average (Alessio *et al.* 2002). The frequency domain estimators are based on the spectrum definition and among the most popular ones are GPH estimator (Geweke & Porter-Hudak 1983), average periodogram estimator (Robinson 1994), log-periodogram estimator (Beran 1994; Robinson 1995a) and local Whittle estimator (Künsch 1987; Robinson 1995b). Due to very specific statistical properties of the electricity prices that have been mentioned in the previous sections and are also discussed in the following section, we opt for the detrended fluctuation analysis which has desirable properties for such type of analysis. As a control estimator, we choose the GPH estimator.

### 2.3.2 Detrended fluctuation analysis

Detrended fluctuation analysis (DFA) of Peng *et al.* (1993; 1994) is a special case of the multifractal detrended fluctuation analysis (MF-DFA) introduced by Kantelhardt *et al.* (2002). For better understanding of the procedure, we present the more general MF-DFA as an initial step.

Let's have a time series  $\{x_t\}$  with  $t = 1, \dots, T$  where  $T$  is a finite time series length. The profile  $X(t)$  is constructed as

$$X(t) = \sum_{i=1}^t (x_i - \bar{x}) \quad (2.1)$$

where  $\bar{x} = \frac{1}{T} \sum_{t=1}^T x_t$  is a time series average. The profile is then divided into  $T_s \equiv \lfloor T/s \rfloor$  non-overlapping windows with length  $s$  (scale) where  $\lfloor \cdot \rfloor$  is a lower integer part operator. As  $T_s$  is not necessarily equal to  $T/s$ , part of the time series is left at the end of the series. In order not to lose the information of this segment, the profile is also divided from the opposite end and both sets of blocks of length  $s$  are further utilized (we thus get  $2T_s$  windows of length  $s$ ).

In each of these  $2T_s$  segments, we calculate the mean squared deviation from the trend of the series in this particular window. This means that for the  $k$ th window, the mean squared deviation  $F^2(k, s)$  is obtained as

$$F^2(k, s) = \frac{1}{s} \sum_{i=1}^s (X(s[k-1] + i) - \widehat{X}_k(i))^2 \quad (2.2)$$

where  $\widehat{X}_k(i)$  is a polynomial fit of a time trend at position  $i$  in window  $k$ . In our application, we utilize a linear fit obtained via the ordinary least squares regression which is standard for the DFA and MF-DFA procedures (Hu *et al.* 2001; Grech & Mazur 2005; Kantelhardt 2009; Kristoufek 2010). This is applied for windows  $k = 1, \dots, T_s$ , and then for windows  $k = T_s + 1, \dots, 2T_s$ , we obtain

$$F^2(k, s) = \frac{1}{s} \sum_{i=1}^s (X(T - s[k - T_s] + i) - \widehat{X}_k(i))^2. \quad (2.3)$$

The multifractal analysis stems in scaling of the  $q$ th order fluctuations so that we need to find behavior of fluctuations at scale  $s$  for different values of order  $q$ . To do so, we construct the  $q$ th order fluctuation function

$$F_q(s) = \left( \frac{1}{2T_s} \sum_{k=1}^{2T_s} [F^2(k, s)]^{\frac{q}{2}} \right)^{\frac{1}{q}}. \quad (2.4)$$

For  $q = 0$ , the zeroth order fluctuation function is defined as

$$F_0(s) = \exp \left( \frac{1}{4T_s} \sum_{k=1}^{2T_s} \log[F^2(k, s)] \right). \quad (2.5)$$

Order  $q$  can take any real value. For  $q = 2$ , the MF-DFA procedure reduces to DFA and it is used to analyze long-term memory properties of series  $\{x_t\}$ . Later in the text, we label  $H \equiv H(2)$ . For other values of  $q$ , the interpretation is not so straightforward but the scaling behavior dependence on  $q$  is a basis of the multifractal analysis which we do not discuss here. In practice, minimum and



maximum scales  $s_{min}$  and  $s_{max}$  need to be set as for finite series, the averaging and trend fitting procedures can become unreliable. Standardly, the minimum scale is set as  $s_{min} \approx 10$  and the maximum scale as  $s_{max} = T/4$  to avoid inefficient trend fitting for low scales and imprecise averaging at high scales.

### 2.3.3 Useful properties of MF-DFA

Estimation of the long-term memory parameters  $H$  has a long history starting from Hurst (1951). Since then, many methods have been developed to study the power-law scaling of the autocorrelation function and the connected phenomena of the divergent at origin spectrum and the power-law scaling of variance of the partial sums. The estimators are developed in both time and frequency domains (see Taqqu *et al.* (1995); Taqqu & Teverovsky (1996); Di Matteo (2007) for reviews of various methods).

As the MF-DFA method can be labelled as the most frequently used method of the multifractal analysis, its strengths and weaknesses have been also given an appropriate focus in the literature. None of the other methods have been studied in such detail. For our purposes, we are mainly interested in the ability of MF-DFA to deal with cycles and heavy-tailed distributions.

Hu *et al.* (2001) discuss the effect of trends on the properties of the detrended fluctuation analysis and a special attention is given to periodic cycles. For long-term memory processes combined with a sinusoidal trend, they show that the scaling  $F_2(s)$  undergoes several cross-overs (changes in scaling rules) due to interaction between long-term memory and sinusoidal trend. For both persistent and anti-persistent series, the scaling passes through three cross-overs and the scaling laws connected to the long-term memory effects are observed for scales  $s$  below the first and above the third cross-over scales. This way, it is possible to distinguish between the effect of long-term memory and sinusoidal trends. Importantly, the authors show that for the anti-persistent processes, the third cross-over scale is frequently higher than  $T/4$  or even  $T$  so that the long-term memory scaling needs to be obtained only from the scales below the first cross-over.

Barunik & Kristoufek (2010) study the effect of heavy tails on the most frequently used heuristic methods of the Hurst exponent estimation. They show that DFA is unbiased regardless of how heavy the tails are. For MF-DFA, they are interested in the case of  $q = 1$  and uncover that for reasonable tails (with tail parameter between 1.5 and 2 where the value of 2 is connected

to the Gaussian distribution and the value of 1 for the Cauchy distribution), the estimates of  $H(1)$  are practically unbiased as well.

In the original study, Kantelhardt *et al.* (2002) also discuss the possibility of highly anti-persistent processes with  $H$  close to 0. In such situations, practically all estimators become severely upward-biased. However, the MF-DFA methodology is constructed for both asymptotically stationary and non-stationary processes. In practice, series  $\{x_t\}$  can be integrated to a new series  $\{y_t\}$  defined as  $y_t = \sum_{i=1}^t x_i$  for  $t = 1, \dots, T$  and MF-DFA can be applied on  $\{y_t\}$ . Labeling the generalized Hurst exponent of the series  $\{x_t\}$  as  $H_x(q)$  and the generalized Hurst exponent of the integrated series  $\{y_t\}$  as  $H_y(q)$ , it holds that  $H_x(q) = H_y(q) - 1$ . Therefore, if  $\{x_t\}$  possesses properties resembling strong anti-persistence, the generalized Hurst exponent for the series can be obtained from running MF-DFA on the integrated series and reducing the estimate by 1.

DFA as a special case of MF-DFA is thus an ideal candidate for the long-term memory analysis of the electricity prices as the above mentioned properties match with the properties of the electricity prices discussed in the previous sections as well as in the next section dealing with specific properties of the Czech electricity spot prices. Before we turn to the dataset description and results, we introduce the control estimator.

### 2.3.4 Alternative estimators

Probably the most severe disadvantage of the MF-DFA and DFA estimators is their lack of asymptotic properties. To cover this issue, we also include two frequency-based estimators – original GPH and GPH with a smoothed periodogram. Apart from the fact that both have well defined asymptotic properties, we also use them to stress superiority of the DFA approach in such a complex matter as the electricity prices. We assume that the frequency-based estimators will not be able to deliver reliable results as their parametric specification is too strict.

GPH estimator (Geweke & Porter-Hudak 1983) is based on a full functional specification of the underlying process as the ARFIMA(0, $d$ ,0) process with a specific spectral form:

$$f(\lambda) \propto |1 - \exp(-i\lambda)|^{-2(H-0.5)} = (4 \sin^2(\lambda/2))^{-(H-0.5)} \quad (2.6)$$

The spectrum  $f(\lambda)$  is estimated using the periodogram and the Hurst exponent is estimated using the ordinary least squares on

$$\log I(\lambda_j) \propto -(H - 0.5) \log(4 \sin^2(\lambda_j/2)). \quad (2.7)$$

The estimator is consistent and asymptotically normal (Beran 1994), specifically

$$\sqrt{T}(\hat{H} - H^0) \rightarrow_d N(0, \pi^2/6). \quad (2.8)$$

As the periodogram is not a consistent estimator of the spectrum, Reisen (1994) and Reisen *et al.* (2000) propose to apply the smoothed periodogram for the estimation procedure (see both references for more details on smoothing). We use both methods. Major issue of the frequency-based estimators such as GPH is the fact that the underlying series need not follow the assumed process specification. In the case of GPH, this is a simple ARFIMA(0, $d$ ,0). However, we show that the correlation structure of the electricity series is very complicated in the following sections and it is thus oversimplified to assume so. Moreover, assuming such specification incorrectly expectedly yields biased estimates. To at least partly overcome this issue, Robinson (1995b) and Phillips & Shimotsu (2004) propose to utilize only a part of the periodogram for the estimation of the Hurst exponent in Eq. 2.7. The part of periodogram taken into consideration  $m$  is usually taken as a root of the time series length  $T$  so that  $m = T^\eta$  where parameter  $\eta$  varies between 0 and 1. The asymptotic properties then change to

$$\sqrt{m}(\hat{H} - H^0) \rightarrow_d N(0, \pi^2/6). \quad (2.9)$$

The estimator thus becomes less efficient but it is less sensitive to the bias at high frequencies. The estimates of the Hurst exponent are then drawn against varying  $m$  to see whether the estimates stabilize at some point so that the correct estimate can be identified.

## 2.4 Data description

We analyze hourly electricity day-ahead spot prices<sup>2</sup> in the Czech Republic between 2009 and 2012, namely 1.1.2009 - 30.11.2012, with a total of 34,316

<sup>2</sup>OTE – the electricity market operator in the Czech Republic – runs four trade platforms – block market, day-ahead spot market, intra-day market and balancing market with regulating energy. For more information, see the Product Sheet at <http://www.ote-cr.cz/about-ote/main-reading>.

Table 2.1: Descriptive statistics

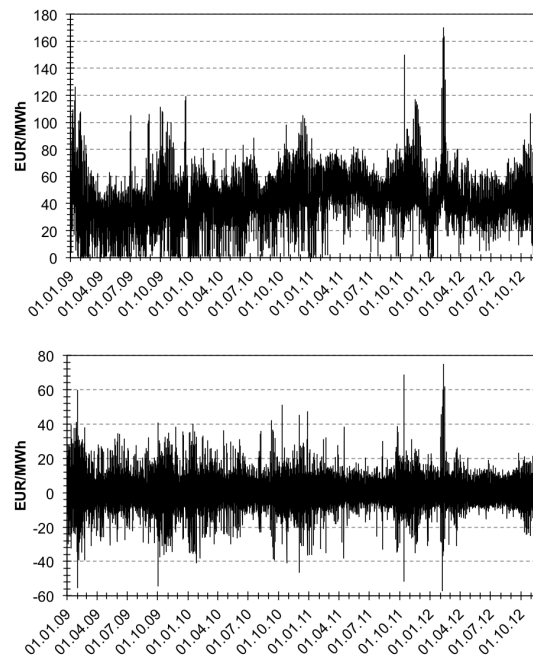
	price	change in price
mean	43.7700	0.0001
SD	16.2551	6.6093
skewness	0.1040	0.4136
excess kurtosis	1.6686	7.4503
Shapiro-Wilk test	14.9120	19.6280
$p$ -value	< 0.01	< 0.01
Jarque-Bera test	4041	80315
$p$ -value	< 0.01	< 0.01
ADF - test (50)	-13.9594	-36.1585
$p$ -value	< 0.01	< 0.01
KPSS (50)	8.7456	0.0012
$p$ -value	< 0.01	> 0.1

observations<sup>3</sup>. The prices are denominated in EUR per MWh and negative prices were not allowed before 2013. In Fig. 2.1, we show evolution of prices during the analyzed period. It is evident that prices jump frequently in both directions. The first differences of the prices strongly resemble standard returns of stocks or exchange rates with volatility clustering and extreme movements. The first differences are far from being normally distributed as shown in Fig. 2.2. However, the original price series are close to normally distributed if we omit the fact that the prices are censored from below. Overall non-normality of distributions is supported by Shapiro-Wilk (Shapiro & Wilk 1965) and Jarque-Bera (Jarque & Bera 1980; 1981) tests in Table 3.2 which shows strong rejection of normality for both series. Standard descriptive statistics support only mild heavy tails of prices but heavy tails for the first differences. Both series are positively skewed so that the more extreme upward movements are more likely. However, the skewness of prices is very close to zero hinting symmetry which is again in hand with the histograms in Fig. 2.2.

For the analysis of dynamics of the series, distinguishing between stationary and non-stationary series is crucial. To this point, we utilize the ADF (Dickey & Fuller 1979) and KPSS (Kwiatkowski *et al.* 1992) tests. The null hypothesis of the former is a unit root against no unit root whereas for the latter, the hypothesis of stationarity against non-stationarity is tested which provides an ideal combination of tests. Results presented in Table 3.2 give an evidence that the price series are non-stationary but do not contain a unit root whereas

<sup>3</sup>Data were obtained from Yearly Reports of OTE available at <http://www.ote-cr.cz/statistics>.

Figure 2.1: Time series plots



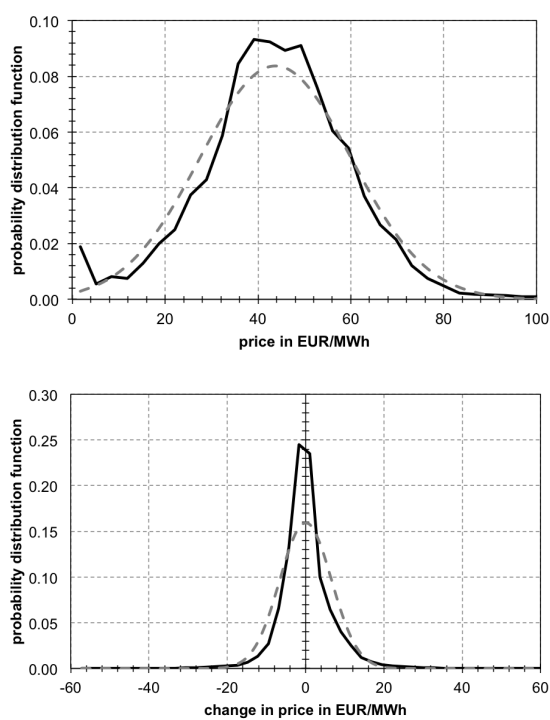
Electricity hourly prices (upper) and their changes (lower) are shown. The changes resemble returns of various financial assets whereas dynamics of the prices is much further from these.

the first difference series are stationary. In terms of the long-term memory notation, the prices of electricity are in the interval  $1 < H < 1.5$  and thus the first differences in  $0 < H < 0.5$ . We thus follow with analysis of prices and not the first differences due to three reasons. Firstly, we do not want to lose information about the dynamics of the prices which would be done by first differencing. Secondly, the price series are much more interesting in the electricity context, there are no actual returns to the series as it is not possible to buy a MWh of electricity and sell it the following period. And thirdly, the expected anti-persistence of the first-differenced series might cause the estimates of Hurst exponent to be biased whereas for the price series, DFA provides more reliable results.

The memory properties of the electricity prices are further illustrated by sample auto-correlation function and periodogram<sup>4</sup> in Fig. 2.3. There, we observe that the dynamics of the prices is very cyclical with a dominating frequency of 24 hours. Both the auto-correlation function and periodogram

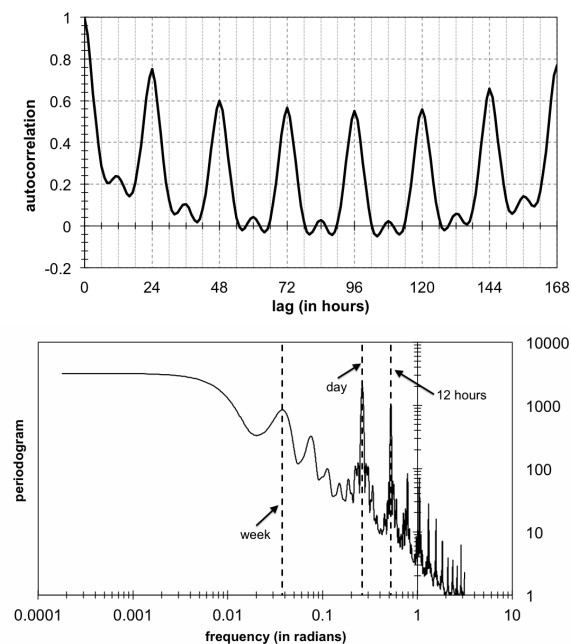
<sup>4</sup>Periodogram is based on Bartlett weights with a bandwidth of 370, i.e. approximately 0.1 of the time series length.

Figure 2.2: Histograms of electricity prices and changes in prices



Probability distribution function of prices (upper, in black) is quite close to the normal distribution (dashed grey line) with the exception of the censored left tail (no negative prices in the sample). Changes in prices (lower) are much further from normality.

Figure 2.3: Correlation structure of prices



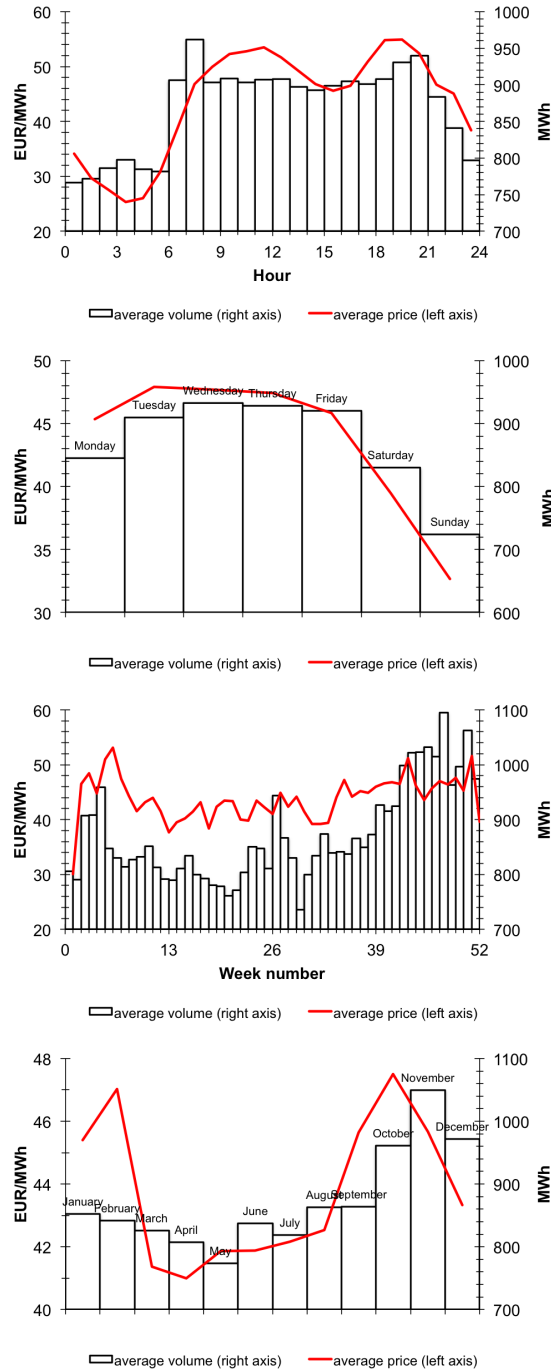
Both autocorrelation function (upper) and periodogram (lower) show strong seasonal component with a dominating scale of 24 hours.

are well in hand with the definitions of long-term memory. However, we can see that both the power-law decay of the auto-correlation function and the power-law divergence at the origin of the periodogram are disturbed by the aforementioned cyclical properties. Due to this fact, we utilize DFA to analyze the long-term memory properties of the series as discussed in the previous section. The complex cyclicity is further illustrated in Fig. 2.4 where we show how the average price and average traded volume depend on an hour of the day, day of the week, and week and month of the year. This again calls for a robust method of the Hurst exponent estimation as discussed previously.

## 2.5 Results and discussion

As shown in the previous section, the correlation structure of the electricity prices in the Czech Republic is very complicated. To control for the most evident seasonalities, we analyze the hourly prices which control for the intraday patterns. Specifically, we standardize the first differences of the prices in a way that the mean value for the given hour of the day is subtracted, the difference is then divided by the standard deviation of the first differences for

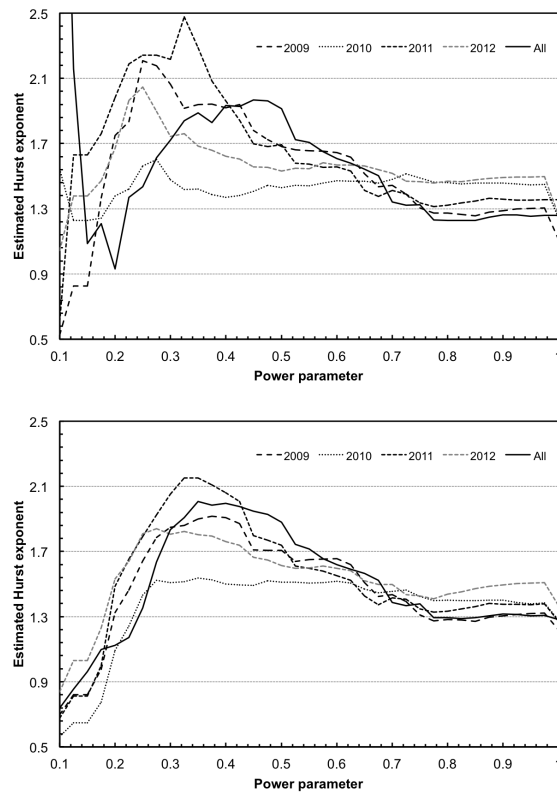
Figure 2.4: Cyclical properties of electricity prices and volumes



Seasonal patterns are shown for intraday (first), daily (second), weekly (third) and monthly (fourth) scales. Apart from the weekly scale, both prices and volumes show pronounced seasonal patterns.



Figure 2.5: GPH estimates of Hurst exponent



GPH (upper) and GPH based on smoothed periodogram (lower) are shown for varying  $m$  where  $m = T^\eta$ . The power parameter  $\eta$  is shown on the  $x$ -axis. Estimates for both methods vary wildly between  $H \approx 0.5$  (uncorrelated noise) and  $H \approx 2$  (strongly persistent non-stationary non-mean-reverting process).

the given hour. The price series are then formed as an integrated series of these standardized first differences.

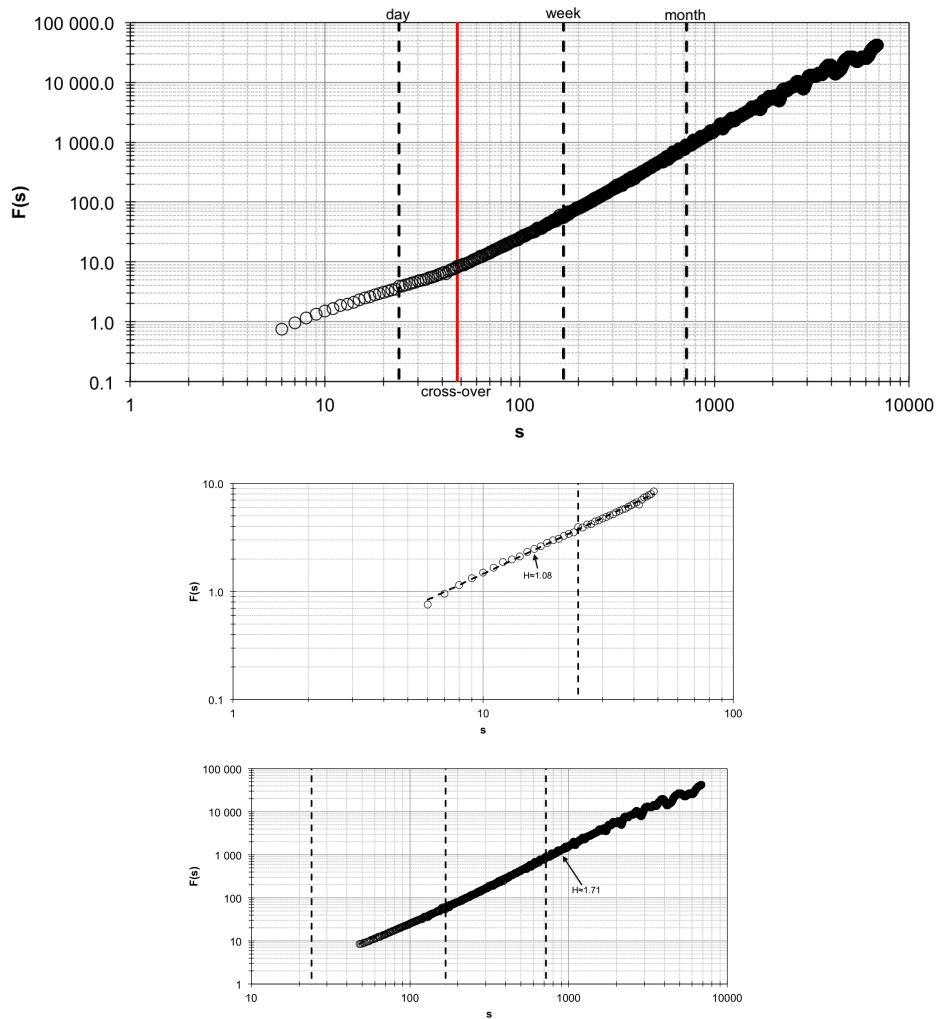
Before turning to the results of the detrended fluctuation analysis, we provide the estimates of Hurst exponent based on GPH and its version based on smoothed periodogram<sup>5</sup>. In Fig. 2.5, we show how the estimates vary with  $\eta$  parameter between 0.1 and 1 with a step of 0.025. Moreover, the results are presented for the whole time period as well as for the separate years. We observe that the estimates fluctuate wildly with changing  $\eta$ . For the original GPH, the estimates vary between  $H \approx 5.1$  and  $H \approx 0.9$  while most of the estimates lay between the Hurst exponent of 1.2 and 2.1. The range is thus very wide and estimates stabilize for  $\eta > 0.7$  at least somehow. However, these estimates are based on almost the whole periodogram where the high frequen-

<sup>5</sup>For this matter, we use the functions *fdGPH* and *fdSperio* in the *fracdiff* package in R-project.

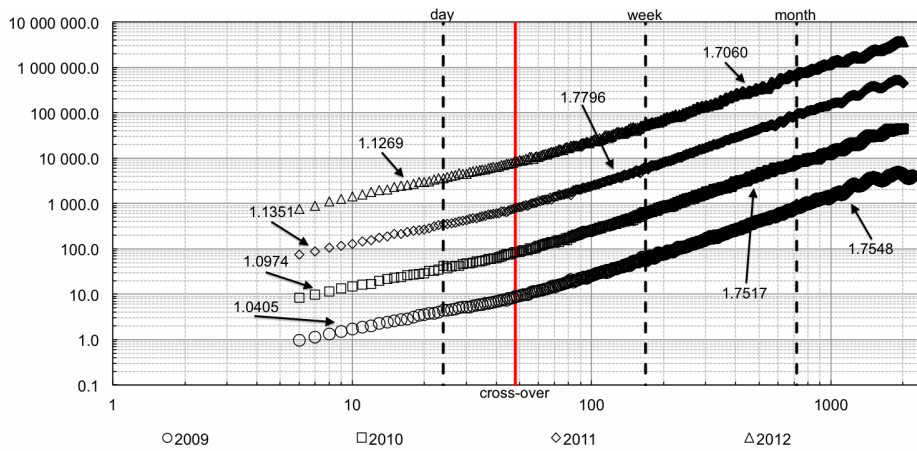
cies (and thus low scales) dominate. Even though the estimates are much less erratic for the smoothed version of GPH, the range of the estimates does not narrow down enough – the estimates range between  $H \approx 0.5$  and  $H \approx 2.1$ . The estimates again stabilize for  $\eta > 0.7$ . Even though the estimated Hurst exponent practically overlap for all years, the GPH approach can hardly be taken as reliable for this specific case of electricity prices and the fact that the estimators have well defined asymptotic properties does not help our analysis at all. These results only stress the need for a more robust estimation technique – the detrended fluctuation analysis.

For the detrended fluctuation analysis, i.e. multifractal detrended fluctuation analysis with  $q = 2$ , we set  $s_{min} = 6$  and  $s_{max} = T/4$  to obtain scaling of the fluctuation  $F_2(s)$  illustrated in Fig. 2.6. As the data frequency equals to one hour, the minimum scale is set at a quarter of a day and the maximum scale approximately matches a year. Based on the initial analysis of the series in the Data description section, we assume that the series contain strong cycles but might also possess long-term memory. It is thus reasonable to assume that the scaling of  $F_2(s)$  contains at least one cross-over. This is indeed true for the analyzed electricity prices as shown in Fig. 2.6. We observe one evident cross-over at  $s_\times \approx 48$ . The cross-over splits the scaling chart into two laws which resemble a power-law scaling strongly as shown in the split charts in Fig. 2.6. This gives two Hurst exponents –  $H \approx 1.1$  for  $s \leq 48$  and  $H \approx 1.7$  for  $s \geq 48$ . Note that these Hurst exponents do not differ considerably for varying  $s_\times$  between 36 (1.5 day) and 72 (3 days) and these are thus quite stable. This multi-scaling can be attributed to competing effects of the long-term memory and periodic trends which are both strong parts of dynamics of the electricity prices. As discussed in the previous section, the Hurst exponent based on scales below the first cross-over scale  $s_\times$  can be used for interpretation of the long-term memory. Therefore, the price dynamics is characterized by  $H \approx 1.1$  and the prices are thus strongly persistent and non-stationary but still remain well below the unit-root level of  $H = 1.5$  so that they remain mean-reverting. This is well in hand with the basic description in Tab. 3.2.

The persistence of the series implies that prices follow rather long-lasting trends, which are even above standard long-term memory with  $0 < H < 1$  making the prices non-stationary. Nonetheless, the dynamics is far from the unit-root behavior and the prices return to their long-term levels. Such behavior is very different from other financial assets which usually follow a random walk and their returns are thus unpredictable (or at least not systematically

Figure 2.6: Scaling of fluctuations  $F(s)$ 

The upper panel shows the scaling of the fluctuation function and a pronounced cross-over at approximately two days. The lower panels show the scaling for both regimes in more detail. The middle panel characterized by  $H = 1.08$  is attributed to the long-term memory of the prices process and the lower panel shows scaling for the scales dominated by cyclical components.

Figure 2.7: Scaling of fluctuations  $F(s)$  for separate years

Estimated Hurst exponents are shown for two scaling regimes for separate years between 2009 and 2012. Scaling exponents are remarkably stable.

predictable). However, we need to keep in mind that such a persistence of electricity prices cannot be easily exploited for profit. The persistence can be also seen as a product of incorrect expectations about a future need for electricity of the market participants. Remembering that the electricity spot market exists to cover the unexpected demand for electricity (as the majority of supplied electricity is based on medium- and long-term contracts), the extreme price movements are mainly caused by external unexpected events (temperature, humidity, macroeconomic news, etc.). When the unexpected event comes, it usually has a medium- or long-lasting effect (e.g. temperature above long-term averages is usually characteristic for whole day or even longer periods) but the traders cannot “pre-buy” the electricity quickly. To cover the increased demand, additional (and usually more expensive) power sources need to be connected to the network which increases the electricity prices. The combined effect of non-storability and connecting less efficient power sources pushes the electricity prices to the persistent behavior.

To see whether these properties are stable in time, we analyze the long-term memory components in the same way but for the separate years 2009-2012. In Fig. 2.7, we observe that the Hurst exponent connected to the long-term memory is rather stable and approximately around 1.1 for all the price series. For the higher scales, we again see stability of the scaling exponent around 1.75. The non-stationary mean-reverting persistence is thus observed even for separate years. Note that only the very specific characteristics of the DFA

method allow us to study the long-term memory without arriving at spurious results. Standardly, the Hurst exponent connected to the higher scales would be reported. However, the difference between having  $H < 1.5$  and  $H > 1.5$  is crucial. For the former, the prices return to their long-term mean. But for the latter, the prices would explode. Note that having  $H \approx 1.1$  implies that the mean reversion is very rapid. These characteristics are very stable in time which is agains results for Ontario and Alberta markets as shown by Alvarez-Ramirez & Escarela-Perez (2010). The results are then somewhere between stationary electricity prices in the USA reported by Park *et al.* (2006) and for Alberta by Urtskaya & Serletis (2008) and almost unit-root prices of the Nord Pool market found by Simonsen (2003).

## 2.6 Conclusion

We have analyzed long-term memory properties of hourly spot prices of the Czech electricity between 2009 and 2012. As the electricity prices have very intriguing properties, such analysis is rather challenging. We have shown that the Czech prices follow similar patterns observed for other electricity prices, mainly intraday, daily and monthly seasonality in both prices and volume. Utilizing the detrended fluctuation analysis, we have been able to separate these cyclical properties from the long-term memory. The results are in hand with majority of the relevant literature as we show that the electricity prices are non-stationary but mean-reverting so that their behavior is partly predictable. However, due to specific features of electricity (mainly its non-storability), such a predictable behavior cannot be easily exploited for earning profits. The electricity prices are thus very different from standard financial assets such as stocks or exchange rates and they need to be treated accordingly. The found patterns of behavior of the electricity prices can be attributed to their structure as the spot prices have been analyzed. These serve mainly to balance demand for electricity which has not been covered by futures contracts. As such, the unexpected change in demand for electricity is rather short-lived and the reversion to a long-term price is quite rapid which is represented by the Hurst exponent close to (but higher than) unity. Stability of the results in specific years and correspondence to the results of more developed markets underline that the Czech electricity market has reached a similar levels of development.

## **Acknowledgments**

The support from the Czech Science Foundation under Grants 402/09/0965 and P402/11/0948, and project SVV 267 504 is gratefully acknowledged.

## Chapter 3

# Rockets and feathers meet Joseph: Reinvestigating the oil-gasoline asymmetry on the international markets

**Published as:** Křišťoufek, Ladislav and Luňáčková, Petra (2015): “Rockets and feathers meet Joseph: Reinvestigating the oil-gasoline asymmetry on the international markets.” *Energy Economics* 49: pp. 1-8.

**Abstract:** We reinvestigate the “rockets and feathers” effect between retail gasoline and crude oil prices in a new framework of fractional integration, long-term memory and borderline (non)stationarity. The most frequently used error-correction model is examined in detail and we find that the prices return to their equilibrium value much more slowly than would be typical for the error-correction model. Such dynamics is usually referred to as “the Joseph effect”. The standard procedure is shown to be troublesome and we introduce two new tests to investigate possible asymmetry in the price adjustment to equilibrium under these complicated time series characteristics. On the dataset of seven national gasoline prices, we find no statistically significant asymmetry. The proposed methodology is not limited to the gasoline and crude oil case but it can be utilized for any asymmetric adjustment analysis.

Keyword: rockets and feathers, asymmetry, gasoline, crude oil, cointegration

*JEL codes: Q40, Q43, Q48*

## 3.1 Introduction

Gasoline prices shoot up like rockets and fall down slowly like feathers – such is a popular belief and a feeling of retail customers at gasoline stations. Increasing gasoline prices in the last decade have made such notion even more relevant to general public as well as to policy makers. The study of Bacon (1991) has coined the term “rockets and feathers” into the literature and since then, the topic has attracted much attention. The price of gasoline, after controlling for taxes, is primarily driven by the crude oil prices, even though such effect is indirect as there are usually several steps from the oil rigs and wells to the retail customers. Although the passthrough of the oil price to the retail gasoline prices might take relatively a long time, due to economic reasons such as transportation, menu costs, storage and others, the price adjustment should be symmetric whether the oil prices are going up or down. Mandelbrot & Wallis (1968) refer to such long-term dynamics as the Joseph effect inspired by the biblical story of Joseph (son of Jacob) who interpreted a dream of the Egyptian pharaoh about upcoming seven years of plenty followed by seven years of famine (Chapter 41 of the Book of Genesis). The dream-telling had been rewarded and Joseph served as the pharaoh’s vizier. The years of plenty and the years of famine represent long periods when time series are above or below their long-term mean. From an econometric standpoint, this is represented by a slow decay of autocorrelation function of the long-term correlated<sup>1</sup> (long-range correlated, or persistent) series (Beran 1994; Samorodnitsky 2006).

Even though the parallel between price adjustment and the Joseph effect might be vivid and straightforward, it does not reflect the approach taken in majority of the empirical literature investigating the “rockets and feathers” effect in the gasoline market. In Section 2, we present a comprehensive literature review of the asymmetric price adjustment between gasoline and crude oil and we show that the studies usually begin with the assumption of the long-term equilibrium relationship between retail gasoline (or diesel in some cases) and crude oil. Specifically, the cointegration relationship is being built upon. This is well grounded both theoretically and empirically. However, the

---

<sup>1</sup>Specifically, the autocorrelation function  $\rho(k)$  (with lag  $k$ ) of long-term correlated series decays as  $\rho(k) \propto k^{2H-2}$  for  $k \rightarrow +\infty$ . Hurst exponent  $H$  represents a strength of the long-term correlations. A time series is standardly labelled as long-term correlated for  $H > 0.5$ . Such process follows long-lived deviations from its mean, yet still reverts back to it for  $H < 1.5$  (a random walk process has  $H = 1.5$ ). This type of a process has been historically labeled as “the Joseph effect” (Mandelbrot & Wallis 1968) due to its long-term behavior, similar to the biblical reference.



next step usually stems in estimating some form of an error-correction model. The deviation from equilibrium, represented by the error-correction term in the cointegration equation, is thus assumed to return to zero, i.e. the equilibrium state, rather quickly. We describe the cointegration and error-correction models methodology in Section 3. There, we also introduce the analyzed dataset, which comprises of the gasoline markets of Belgium, France, Germany, Italy, the Netherlands, the UK and the USA, and we focus on the basic dynamic properties of the series as well. We show that the gasoline markets are indeed cointegrated with crude oil. However, we also show that gasoline prices return to their long-run equilibrium very slowly. Specifically, we show that such dynamics can be attributed to long-term correlations and hence the Joseph effect rather than to the rapidly adjusting error-correction model. We argue that such a strong memory makes the standard error-correction models and their variants infeasible. As a solution, we propose two new tests for examining asymmetry in the cointegration framework. In Section 4, we present results of the asymmetry testing on the international gasoline markets and we show that there is no statistical evidence of the “rockets and feathers” dynamics towards equilibrium, and we also outline possible directions of future research in this area. Section 5 concludes.

## 3.2 Literature review

The term “rockets and feathers” has been connected with crude oil and retail gasoline since 1991 when Robert Bacon published his famous article (Bacon 1991). Since then, vast research focusing on the (a)symmetric behavior of prices “at the pump” has been performed. Its motivation is to explain this phenomenon and understand whether any policy would improve the current market situation. As the literature on the topic is quite broad, we summarize the reviewed articles in Tab. 3.1 while focusing mainly on the analyzed time period, location and possible asymmetry.

The most common econometric approach investigating the asymmetry is the error-correction model (ECM). We focus on this dominant branch of the literature. All the ECMs are based on the two step Engle & Granger (1987) procedure that exploits the long-run equilibrium relationship between, in our case mostly, crude oil and retail gasoline. Various ECM specifications could be put into three groups – asymmetric ECM (used by most studies), threshold autoregressive ECM (Godby *et al.* 2000; Al-Gudhea *et al.* 2007) and ECM with

threshold cointegration (Chen *et al.* 2005). For more detailed analysis, see the work of Grasso & Manera (2007) who study the sensitivity of various ECM models in order to understand how the choice of a particular model influences the results.

Existing literature differs by a country, a sample period and a data frequency, an econometric model and a research question. Paper of Borenstein *et al.* (1997b) has influenced all subsequent papers and it serves as the reference point until now. The study is focused on the US market in 1986-1992 and its findings are based on ECM. The authors provide evidence for a common belief that after a crude oil price changes, gasoline prices rise faster than they fall. They try to identify the stage where the asymmetry occurs but it seems to be spread over all stages. The paper also offers an explanation for the asymmetric retail price adjustment (sticky prices, production lags, and inventories).

Balke *et al.* (1998) extend the previous study using several different model specifications and they confirm the asymmetry and conclude that the findings are sensitive to model specifications but not to the sample period. Bachmeier & Griffin (2003) use daily (spot) prices from the US market and find no evidence of asymmetry in wholesale gasoline prices. Analysis of Borenstein *et al.* (1997b) is performed on weekly and biweekly data and that is how Bachmeier & Griffin (2003) explain different results – broader interval can result in a significant bias.

The literature on the “rockets and feathers” phenomenon can be viewed and compared from many different angles. Firstly, the studies can be divided according to a country of interest. Most of the studies focus on the US market, some on Canada and the UK, few on Western European countries, other countries like Chile (Balmaceda & Soruco 2008) or New Zealand (Liu *et al.* 2010) are studied only rarely. According to Duffy-Deno (1996), the asymmetric effect depends also on the market size, and conclusions made based on local markets’ data cannot be generalized and applied to national markets. Deltas (2008) also relates the asymmetry to the local market conditions. Secondly, according to the objective, the articles’ aim is to (dis)prove the asymmetry or to analyze the asymmetry itself. Thirdly, a sample period and a data frequency matter, and mainly the latter one that varies from daily to monthly, and various specifications (simple price averages or prices collected on a specific day of the week) are utilized. For example, Bettendorf *et al.* (2003) estimate the ECM for five datasets, one for each working day, to find out whether the choice of a weekday matters. Fourthly, according to the results, asymmetry prevails but

it is not unanimous. Godby *et al.* (2000) work on Canadian data and, together with Bachmeier & Griffin (2003) and Karrenbrock (1991), they are among few authors who cannot reject symmetry. The three mentioned studies that report no asymmetry all worked with different data frequency which suggests that frequency may not be the crucial factor. Some findings are also neutral as in Bettendorf *et al.* (2003) or Oladunjoye (2008). From a different angle, Douglas (2010) claims that the uncovered asymmetry is caused by outliers in the analyzed dataset. The asymmetry disappears when the outliers are excluded.

Last but not least, we can split the articles according to the approach that explains the asymmetry as all papers discuss the causes of the asymmetry as well. There are three major explanations. The first one focuses on market power and connects the phenomenon to the oligopolistic theory. Market power is the most widespread explanation. Price of retail gasoline is easily available and of interest to all drivers, which is a large group of consumers that frequently suspect some form of a collusion, even though there is little evidence of the market power abuse (Brown & Yücel 2000). Moreover, even if there was a player with a significant market power, Peltzman (2000) does not find any link between market power and asymmetric pricing. On the contrary, Radchenko (2005) attributes asymmetry to the oligopolistic theory and finds negative relation between oil price volatility and asymmetric response of gasoline prices – a degree of asymmetry declines with an increase in oil price volatility.

The second explanation analyzes the demand side of the market and claims that consumers cause part of the asymmetry, a theory known as the consumer search theory. Consumers search less intensively for a better deal when prices are falling. Imagine a driver passing by a gas station who spots gasoline rack prices and now gasoline costs less than he expected. If our hypothetical driver is in a need of gasoline, he will stop at that station (and observe others' prices as he goes his way). In his theoretical paper, Tappata (2009) suggests that the asymmetric response emerges naturally, based on consumer search. Lewis (2011) also says that consumers search less when prices are falling, the reduced search causes a slower price response. Johnson (2002) gives the following implication – if search costs are such an important factor that determines the lag length, then there should be a shorter adjustment lag in the case of diesel than in the case of gasoline, as diesel is typically bought in larger quantities and more frequently so that the customers have a greater incentive to search.

Other (minor) explanations form the third group. Decreasing inventories are the reason to either produce less (resulting in a price increase) or buy more

inputs (resulting in a price increase as well). Unfortunately, the opposite does not have to hold for an increasing amount of inventories which adjust more slowly. The intention is to avoid abrupt price changes and not to increase an already high price volatility. The FIFO (first in first out) accounting principle built in the pricing process does not smooth the price/costs changes and refinery adjustment costs either, it follows the behavior of inventories. Gasoline prices respond to cost shocks with a lag in order to spread the adjustment costs (Borenstein & Shepard 2002).

Panagiotidis & Rutledge (2007) test the assumption that liberalization should cause decoupling of gas and oil prices on the British data. Their results do not support the expectations, which on the contrary support the cointegration relation of crude oil and retail gasoline. Galeotti *et al.* (2003) revisit the phenomenon analyzing an international data set (joint data for France, Spain, Italy, Germany and the United Kingdom) and break up the process into two stages – refinery and distribution. In both cases, asymmetry is found. Verlinda (2008) then focuses on a local market, believing in its greater information value. Employing a detailed weekly data at a station level and local market characteristics, the author concludes that the degree of asymmetry is influenced by a brand identity, a proximity to rivals, local market features and demographics.

Reilly & Witt (1998) focus on the work of Bacon (1991) and their findings do not support those of Bacon who claims the upward price process to be slightly faster and the period of adjustment more concentrated than in the case of downward price movement. According to Reilly & Witt (1998), both price changes are fully passed through in the long-run. Eckert (2002) studies the Canadian data (Windsor, Ontario) and rejects a tacit collusion as the explanation of asymmetry, and instead points out that retail price series show an asymmetric cycle, which is not present in the wholesale prices series. And finally, Kaufmann & Laskowski (2005) argue that asymmetry is implied by the efficient gasoline markets so that there is little justification for policy interventions.

### 3.3 Data and preliminary analysis

We analyze weekly gasoline prices for Belgium, France, Germany, Italy, the Netherlands, the UK and the USA and their possible asymmetric transmission referred to as the “rockets and feathers” effect in the literature. For the European markets, we utilize the Brent crude oil as an exogenous production

variable, and for the US market, we use the WTI crude oil. The oil prices are the average weekly spot prices and the gasoline prices are the average retail prices for the given country. The whole dataset was obtained from [www.eia.gov](http://www.eia.gov). The analyzed period starts on 08.01.1996 and goes up to 19.5.2014, which gives us 959 weekly prices for each variable.

Evolution of all the analyzed prices is illustrated in Fig. 4.1. The gasoline prices are reported without taxes and in the US dollars per gallon for a better comparison. Crude oil prices are reported in the US dollars per barrel. We observe that the gasoline prices for all countries practically overlap for the whole analyzed period. The same thing can be said about the Brent and WTI crude oils until 2011. However, from 2011 onwards, the WTI price remains below the Brent price due to changes in the US oil policies. Even though the initial divergence of the series is rather sharp, the prices have been converging during the last months.

Traditional “rockets and feathers” literature builds on the assumption that gasoline and crude oil prices are cointegrated, i.e. they tend to a long-run equilibrium, in economic terms. As crude oil prices can be taken as an exogenous variable and all prices are reported in the US dollars, we can write the long-run equilibrium relationship as

$$\log(G_{i,t}) = \beta_0 + \beta_1 \log(CO_{i,t}) + \varepsilon_{i,t} \quad (3.1)$$

where  $G_{i,t}$  is the gasoline price of country  $i$  at time  $t$ ,  $CO_{i,t}$  is the crude oil price respective to country  $i$  at time  $t$ . Due to the logarithmic specification of Eq. 3.1, parameter  $\beta_1$  can be interpreted as a long-term elasticity or a long-term passthrough. Error-correction term  $\varepsilon_{i,t}$  is a deviation from the long-term equilibrium. If the prices return to their long-term equilibrium more slowly from above than from below, the situation is labelled as the “rockets and feathers” effect. Therefore, the analysis of behavior of the error-correction term separately above and below the equilibrium value becomes crucial.

As we have demonstrated in the preceding sections, the typical way how to approach such problem is to treat Eq. 3.1 as the cointegration relationship. If such relationship is found, the authors usually tackle the series using the (vector) error-correction model. Such procedure assumes that the original series  $G$  and  $CO$  are unit roots, i.e. integrated of order one,  $I(1)$ , and the error-correction term is stationary and weakly dependent, i.e. integrated of order

zero,  $I(0)$ <sup>2</sup>. As the cointegration relationship is usually built simply on the prices of gasoline and crude oil, the Engle-Granger two-step cointegration testing procedure is applied (Engle & Granger 1987). The procedure stems in two steps. Firstly, the original series of Eq. 3.1 are tested for unit root using the Augmented Dickey-Fuller (ADF) test (Dickey & Fuller 1979). And secondly, if both the original series are found to contain unit root, the cointegration relationship in Eq. 3.1 is estimated using OLS and the residuals are tested for the unit root presence as well. If the unit root is rejected for the residuals, i.e. the estimated error-correction term, we say that series  $G$  and  $CO$  are cointegrated.

For our dataset, we find straightforward results for the original series, which are summarized in Tab. 3.2 – all the analyzed series contain unit root. In Tab. 3.2, we also apply the KPSS test (Kwiatkowski *et al.* 1992), which has a null hypothesis of  $I(0)$ , i.e. weakly dependent stationarity. The latter test supports the finding of unit roots in all gasoline and crude oil prices. The series are thus eligible for possible cointegration relationships. Estimated long-run elasticities (also standardly referred to as a long-term passthrough or a long-term transmission), together with heteroskedasticity and autocorrelation consistent (HAC) standard errors, are summarized in Tab. 3.3. The long-term transmissions vary between 0.6 and 0.8 and we thus do not observe a complete passthrough of the crude oil price and its changes into gasoline prices for any of the analyzed markets. However, the more important findings are reported in the right part of the table.

There, we report the ADF and KPSS tests for the error-correction terms from all the cointegration relationships, which are illustrated in Fig. 4.2. The results are again quite straightforward – the error-correction terms are not unit root series but are also not stationary (or they are borderline stationary<sup>3</sup>). This is further supported by the estimated  $d$  parameters using the local Whittle<sup>4</sup>

---

<sup>2</sup>A level of integration reflects a number of times the series needs to be difference to become a weakly dependent stationary process, i.e. integrated of order  $I(0)$ . This number is standardly labelled as  $d$ . The parameter  $d$  does not necessarily need to be a finite number. For such case, we speak about fractionally integrated processes as these need to be fractionally differenced to attain  $d = 0$ . The parameter is important for describing dynamic properties of the series. For  $d = 0$ , we have a weakly dependent stationary process, as already noted. For  $d > 0$ , we have a long-range dependent process. Processes with  $d < 0.5$  are stationary and mean-reverting, the ones with  $0.5 \leq d < 1$  are non-stationary but still mean-reverting, and the ones with  $d \geq 1$  are non-stationary and not mean-reverting, i.e. explosive. The fractional differencing parameter  $d$  is tightly connected to Hurst exponent  $H$  from the definition of long-term memory as  $d = H - 0.5$ .

<sup>3</sup>Processes with the fractional integration parameter  $d \approx 0.5$  are usually referred to as borderline stationary.

<sup>4</sup>The local Whittle estimator is a semi-parametric maximum likelihood estimator utilizing

(Robinson 1995a) and the GPH<sup>5</sup> (Geweke & Porter-Hudak 1983) estimators. The estimates and standard errors suggest that most of the error-terms are borderline (non-)stationary with  $0.5 \lesssim d < 1$ . We can thus safely say that all of the analyzed pairs are cointegrated. However, we can also safely state that the error-correction terms are not  $I(0)$ . Even though this does not play any significant part for the cointegration itself, it plays a crucial role in the appropriateness of the error-correction models. Using the notation of Eq. 3.1, we can write the error-correction model (ECM) as

$$\Delta \log(G_{i,t}) = \gamma_0 + \sum_{j=1}^p \gamma_j \Delta \log(G_{i,t-j}) + \sum_{j=1}^p \delta_j \Delta \log(CO_{i,t-j}) + \eta \hat{\varepsilon}_{i,t-1} + u_{i,t}. \quad (3.2)$$

The regression is estimated using the ordinary least squares and parameter  $\eta$  is negative for the cointegration relationship, i.e. the error-correction term reverts back to the mean values and the cointegrated pair does not diverge<sup>6</sup>. The logarithmic differences of the gasoline and crude oil prices are  $I(0)$  automatically, i.e. from the fact that the prices are  $I(1)$ . However, for a feasible estimation procedure, we also need a stationary and weakly dependent error-correction term  $\hat{\varepsilon}_t$ . This is usually assumed from rejection of the null hypothesis of the ADF test, i.e. from the rejection of unit root. However, a rejection of  $I(1)$  does not automatically imply either of  $I(0)$ , stationarity or weak dependence. Figures shown in Tab. 3.3 clearly show that the error-correction term does not meet the necessary criteria for ECM to be correctly estimated. There are various reasons why the estimation procedure in Eq. 3.2 does not work when the error-correction term is not  $I(0)$ . We now shortly focus on the most obvious one.

---

the likelihood function of Künsch (1987) and using a part of spectrum near the origin. Spectrum  $f(\lambda)$  is estimated using periodogram  $I(\lambda)$ . For the time series of length  $T$ , and setting  $m \leq T/2$  and  $\lambda_j = 2\pi j/T$ , the Hurst exponent is estimated as  $\hat{H} = \arg \min R(H)$  where  $R(H) = \log \left( \frac{1}{m} \sum_{j=1}^m \lambda_j^{2H-1} I(\lambda_j) \right) - \frac{2H-1}{m} \sum_{j=1}^m \log \lambda_j$ . The estimator is consistent and asymptotically normal.

<sup>5</sup> The GPH estimator is based on a full functional specification of the underlying process as the fractional Gaussian noise which yields a specific spectral density which is in turn used in the regression estimation of  $\log I(\lambda_j) \propto -(H-0.5) \log[4 \sin^2(\lambda_j/2)]$  using the periodogram in the same way as the previously defined local Whittle estimator.

<sup>6</sup>The error-correction specification allows for distinguishing between a short-run passthrough represented by  $\delta_j$  parameters and a long-run passthrough represented by the parameter  $\eta$ . As we argue here, the ECM specification is infeasible in the crude oil and gasoline market so that the separation between these two effects loses its meaning. We thus strictly focus on the long-run passthrough implied from the original cointegration relationship given by  $\beta_1$  in Eq. 3.1.

Assume that Eq. 3.2 holds and also assume that the error-correction term  $\hat{\varepsilon}_{i,t-1}$  is integrated of order higher than zero, i.e. it is a long-term memory process as reported for our dataset. From the definition of the standard cointegration relationship, we know that both  $\log(G_{i,t})$  and  $\log(CO_{i,t})$  are integrated of order one, i.e.  $I(1)$ . Their first differences are thus automatically  $I(0)$ . Turning now back to Eq. 3.2, we have an  $I(0)$  process (left hand side of the equation) being a sum of three  $I(0)$  processes (gasoline, crude oil and an error term  $u_{i,t}$ ) and one process integrated of order higher than zero. This is a contradiction as the sum of integrated processes is asymptotically integrated of the same order as the highest order among the separate processes (Engle & Granger 1987; Samorodnitsky 2006; Kristoufek 2013). The estimation is thus inconsistent.

Even though we do not replicate the time series analyzed in other studies using ECM and asymmetric ECM, we can quite confidently speculate that the statistical and dynamic properties of the gasoline and crude oil series do not differ much from the ones we report and it is very likely that the same problem exists even for other studies. Application of ECM (or the asymmetric ECM which is popular in the “rockets and feathers” literature) thus yields unreliable results. Any study dealing with the asymmetric passthrough from crude oil to gasoline prices using the cointegration framework should take this issue into consideration. In the next section, we introduce two tests which build on the cointegration methodology and possible asymmetry of the error-correction term. The tests are constructed using the characteristics of the mean-reverting time series and they do not need the analyzed series to be either  $I(0)$  or stationary or weakly dependent.

### 3.4 Methodology

The cointegration framework is a natural environment for analyzing the price transmission from crude oil to retail gasoline. The “rockets and feathers” dynamics of the relationship can be simply understood as the fact that it takes prices a longer time before they converge back to their equilibrium level if gasoline is overpriced (with respect to the cointegration long-term equilibrium) than if it is underpriced. In the previous section, we have shown that the error-correction term, which represents such deviation from the equilibrium state, is fractionally integrated of order less than one which implies that the term is mean-reverting and the gasoline price thus returns to its equilibrium level. We can use the mean reversion approach in the “rockets and feathers” framework



by saying that if the effect is existent on the specific market, then the positive part of the error-correction term will revert to its mean more slowly than the negative part. In this section, we introduce two new tests based on this idea.

### 3.4.1 Wave test

Mean-reverting persistent time series are characteristic by wandering quite far away from the mean value and for long time periods. Labeling values above the mean as + and values below the mean as -, we can obtain a series such as + + + - - - - + + - which consists of four runs - two positive ones with lengths of three and two, and two negative ones with lengths of four and one. Let's say that we have a set of positive runs with given lengths  $W^+$  and a set of negative runs with given lengths  $W^-$ . In the example, we have  $W^+ \in \{3, 2\}$  and  $W^- \in \{4, 1\}$ .

Let's return to the case of error-correction term and its possible asymmetry around the mean value. In the case of symmetry, series both above and below the mean have the same mean-reversion rate so that the length of runs should be on average the same. In the case of the "rockets and feathers" dynamics, the error-correction term should stay longer above its mean value before it returns to its equilibrium level than if it's below its mean value. Utilizing this characteristic, we propose a new test based on a difference between the average length of runs above and below the mean value. As the wandering away from the mean value is rather persistent for this specific case, we rather refer to these persistent runs as waves. This way, we also distinguish between standard runs tests, which are used to test no serial correlation of the series whereas the waves test examines potential asymmetry in the dynamics around the mean value.

The wave testing statistic  $W$  is defined as

$$W = \overline{W^+} - \overline{W^-} \tag{3.3}$$

where  $\overline{W^+}$  is an average length of the positive runs in the error-correction term  $\hat{\varepsilon}_t$  and  $\overline{W^-}$  is an average length of the negative runs. For the symmetric error-correction term, the expected value of the  $W$  statistic is zero whereas for the prevailing positive runs, i.e. the slower mean-reversion of the values above the equilibrium state which corresponds to the "rockets and feathers" effect, the statistic is positive. Therefore, the null hypothesis is stated as  $H_0 : W = 0$  against the alternative of  $H_1 : W > 0$ .

### 3.4.2 Rescaled range ratio test

In the previous section, we show that the error-correction terms for all analyzed series are non-stationary or borderline stationary. Specifically, the fractional differencing parameter  $d$  is very far from  $d = 0$  assumed for standard error-correction models. Even if  $d \gtrsim 0.5$  for all series, which disqualifies the use of standard error-correction models, the notion of fractional integration and long-term memory still provides ways to test for asymmetry in the error-correction term dynamics around its mean. The higher the  $d$  parameter is, the more persistent the underlying series is and thus the more it wanders away from its long-term mean value. Therefore, we assume that the level of persistence is the same for both parts (positive and negative) of the symmetric error-correction term. And for the “rockets and feathers” asymmetry, we would observe that the positive part of the error-correction term is more persistent than the negative part.

However, it turns out that testing for difference in the fractional integration parameters  $d$  of part of one series is much more troublesome than testing the difference between two series. This is mainly due to the nature of the error-correction term  $\hat{\varepsilon}_t$  separation into two series – the positive and the negative ones. The positive part takes the same values of the original series if these are positive and zero otherwise, and symmetrically for the negative part. Each of these series thus has long periods when being equal to zero. This levies a strong autocorrelation structure into the series so that we cannot simply estimate the  $d$  parameters of the separate series and compare these. We cannot even use the two-sample test of Lavancier *et al.* (2010) which is specifically constructed for testing equal  $d$  for two series. To overcome these issues, we introduce a new test.

Motivated by the test of Lavancier *et al.* (2010) which is based on the univariate rescaled variance test of Giraitis *et al.* (2003), we propose a parallel test based on the rescaled range test originally utilized by Hurst (1951) and later studied and popularized by Benoît Mandelbrot (Mandelbrot & Wallis 1968; Mandelbrot 1971; 1972). Similarly to the original method, we construct a range of the series’ profile, i.e. a difference between maximum and minimum of the cumulative deviations from the mean. However, our series have specific properties and the aim of the test is different so that we need to alter the original methodology.

We construct ranges for each part of the error-correction term  $\hat{\varepsilon}_t$  and we la-

bel them as  $R^+$  and  $R^-$  for the positive part and the negative part, respectively. Formally, this is expressed as

$$R^+ = \max \left( \sum_{t=1}^T \hat{\varepsilon}_t \mathbb{I}_{\hat{\varepsilon}_t \geq 0} \right) - \min \left( \sum_{t=1}^T \hat{\varepsilon}_t \mathbb{I}_{\hat{\varepsilon}_t \geq 0} \right) = \sum_{t=1}^T \hat{\varepsilon}_t \mathbb{I}_{\hat{\varepsilon}_t \geq 0} \quad (3.4)$$

$$R^- = \max \left( \sum_{t=1}^T \hat{\varepsilon}_t \mathbb{I}_{\hat{\varepsilon}_t < 0} \right) - \min \left( \sum_{t=1}^T \hat{\varepsilon}_t \mathbb{I}_{\hat{\varepsilon}_t < 0} \right) = - \sum_{t=1}^T \hat{\varepsilon}_t \mathbb{I}_{\hat{\varepsilon}_t < 0} \quad (3.5)$$

where  $\mathbb{I}_{\bullet}$  is an indicator function equal to 1 if the condition in  $\bullet$  is met and 0 otherwise. To take into consideration the fact that the scale of each part differs, we rescale each range using its variance. However, as the series are constructed as the negative and the positive part of the error-correction term, standard variance would introduce bias through its estimated mean value. To control for this specific, we utilize semi-variances of the series rather than variances. If the error-correction term varies symmetrically around its mean value, the rescaled ranges of each part should be the same (asymptotically). In the case of the “rockets and feathers” asymmetry, the rescaled range of the positive part should dominate the other one. This leads us to a construction of the testing statistic, which we label as the rescaled range ratio (RRR) statistic, as

$$RRR = \frac{R^+}{R^-} \times \frac{\sum_{t \in \{t: \hat{\varepsilon}_t < 0\}} \hat{\varepsilon}_t^2}{\sum_{t \in \{t: \hat{\varepsilon}_t \geq 0\}} \hat{\varepsilon}_t^2}. \quad (3.6)$$

As the rescaled ranges serve as a measure of mean-reversion speed, these should be equal for the symmetric case. Therefore, the null hypothesis is stated as  $H_0 : RRR = 1$  against the alternative of  $H_1 : RRR > 1$  as a higher rescaled range signifies a stronger persistence.

### 3.4.3 Statistical testing procedure

Both introduced tests follow a complex behavior under the null hypothesis dependent on a level of long-range dependence as well as distributional properties of the underlying process. Moreover, the tests are applied on a rather short finite sample time series (in our specific case with approximately 1000 observations). Distribution of the testing statistics under the null hypothesis thus needs to be carefully controlled for in the testing procedure.

We follow Hall & Wilson (1991) who introduce a bootstrapping procedure

which ensures a high power of a test, i.e. a high chance of rejection the null hypothesis when in fact the alternative hypothesis is correct, as well as a low error in the significance of the test, i.e. a low probability of rejecting the null hypothesis when it is true.

Let us work with a parameter of interest  $\theta$  and its estimate  $\hat{\theta}$  with variance  $\hat{\sigma}_\theta^2$ . Let us further have a bootstrapped estimate of  $\theta$  under the null hypothesis  $\hat{\theta}^*$  with variance  $\hat{\sigma}_{\theta^*}^2$ . For a selected significance level  $1 - \alpha$ , we find a critical value  $\hat{t}_\alpha$  for which

$$P^* \left( \frac{|\hat{\theta}^* - \hat{\theta}|}{\hat{\sigma}_{\theta^*}} > \hat{t}_\alpha \right) = \frac{\alpha}{2} \quad (3.7)$$

where  $P^*$  stands for probability measure under the bootstrap distribution. The null hypothesis  $H_0 : \theta = \theta_0$  is rejected in favor of the alternative  $H_1 : \theta > \theta_0$  if

$$\frac{\hat{\theta} - \theta_0}{\hat{\sigma}_\theta} > \hat{t}_\alpha. \quad (3.8)$$

As we work with time series rather than randomly sampled cross-sectional data, the bootstrapping procedure gets slightly more complicated (Efron 1987; Kunsch 1989). We cannot simply resample from the original series as this would destroy its correlation structure. We need to simulate a series which has very close dynamic and statistical properties as the original one but in addition, the null hypothesis holds. To do so, we utilize the Theiler's Amplitude Adjusted Fourier Transform (TAAF) (Theiler *et al.* 1992) which ensures that the series has the same correlation structure as the original series as well as distributional properties. Crucially, the method keeps the correlations symmetric as it is based on the Fourier transform. This way, the simulated series has symmetric correlations, which are needed under the null hypothesis, and the same distribution which avoids possible inefficiency of the testing statistics. We simulate 10,000 series using the TAAF procedure for each analyzed series to obtain  $\hat{\theta}^*$  and  $\hat{\sigma}_{\theta^*}$ . Null hypothesis  $\theta_0$  is given for both tests we utilize. We thus still need  $\hat{\theta}$  and mainly  $\hat{\sigma}_\theta$ .

Estimated parameters are obtained using the moving-block jackknife method (Efron & Stein 1981; Kunsch 1989). In the procedure, one fixes the estimating period to  $J$  (in our case we set this period to  $J = 500$ ). A parameter of interest is then estimated on observations  $1, \dots, J = 500$ , then on  $2, \dots, J + 1$ , and so forth. Eventually, we obtain  $T - J + 1$  estimates, where  $T$  is the original time series length. Based on these, we get  $\hat{\theta}$  as an average of the jackknifed estimates and  $\hat{\sigma}_\theta$  as their standard deviation. This gives us all necessary vari-

ables for Eqs. 3.7 and 3.8 and the testing procedure is thus complete. Note again that the described procedure ensures very good statistical properties, specifically the high test power and low significance error as reported by Hall & Wilson (1991).

### 3.5 Application and discussion

In the Data and preliminary analysis section, we have shown that for all the studied gasoline markets (Belgium, France, Germany, Italy, the Netherlands, the UK, and the US), the relationship with the given crude oil (either Brent or WTI) is identified as a cointegration one, i.e. the gasoline and crude oil prices tend to an equilibrium value. The price transmission from crude oil to gasoline varies approximately between 0.6 and 0.8 so that it is quite strong yet still imperfect. Deviations from the long-term equilibrium gasoline prices, which are represented by the error-correction term, have been shown to deviate strongly from an  $I(0)$  process. Such dynamics can be also observed by a naked eye in Fig. 4.2. The term is thus not weakly dependent and mostly on the verge of (non-)stationarity. Furthermore, we have shown that such error-correction term makes standard ECM models invalid. To be able to use the cointegration framework for distinguishing between symmetric and asymmetric dynamics of the error-correction term, we have introduced two new tests in the previous sections. Results of the tests now follow.

Tab. 3.4 summarizes all the results and it includes the testing statistics and  $p$ -values for the null hypothesis of symmetric adjustment of the error-correction term coming from Eq. 3.1 against the one-sided alternative hypothesis of the “rockets and feathers” asymmetry, i.e. the case when the error-correction term reverts to the equilibrium more slowly when its above equilibrium compared to the situation when it is below the equilibrium value. The  $p$ -values are based on the bootstrapping procedure described in detail in the previous section.

The results are very straightforward – we find no “rockets and feathers” dynamics in the analyzed series. Therefore, the long-run passthrough from crude oil to retail gasoline prices shows no signs of asymmetry for our dataset. To show how these results differ from the standardly used ECM framework, we also present the testing statistics for asymmetry based on (Galeotti *et al.* 2003)<sup>7</sup>.

<sup>7</sup>Galeotti *et al.* (2003) constructs an asymmetric ECM model as  $\Delta \log(G_{i,t}) = \alpha + \beta^+ ECM_{t-1}^+ + \beta^- ECM_{t-1}^- + \gamma^+ \Delta \log(CO_{i,t}^+) + \gamma^- \Delta \log(CO_{i,t}^-) + u_{i,t}$  where the superscripts + and – signify whether the series is above or below zero. The testing procedure for the

In the right part of Tab. 3.4, we present the testing statistics and  $p$ -values for the null hypothesis of symmetry against the “rockets and feathers” alternative. The latter is identified for two markets – Belgium and Germany. For others, the null hypothesis cannot be rejected. Such result supports our claim that the ECM framework should be used carefully as the ECM coefficient might be estimated incorrectly, leading to spuriously rejected symmetry. Nevertheless, the research on the topic is of course not complete.

Firstly, we have found no asymmetry at national level. However, more localized study could report qualitatively different results. Secondly, the pair of tests we have newly introduced in this article does not cover all possibilities. There are some other approaches that could be added such as fractionally integrated ECM or fractional cointegration framework in general. And thirdly, we do not investigate various stages of the price transmission. The article thus primarily serves as a starting point for treating the asymmetric equilibrium adjustment of the error-correction term in a different, statistically and econometrically convenient, way. Finally, it has to be noted that the developed tests are not restricted to the relationship between retail gasoline, crude oil and related variables but they can serve to test the asymmetry in any economic and financial application which considers asymmetry in the cointegration framework.

### 3.6 Conclusion

We have analyzed the possible “rockets and feathers” dynamics between the retail gasoline and crude oil prices. Focusing on the national prices of selected countries, we provide a step-by-step treatment in the cointegration framework. The standardly applied error-correction model methodology is discussed in detail. We show that it is not convenient for analysis of the price transmission asymmetry in the given system due to long-term memory aspects of the equilibrium adjustments, which are represented by the error-correction term. We show that the gasoline prices return to their equilibrium levels much more slowly than assumed by the ECM approach which makes the estimation inconsistent, and the results are thus unreliable. To deal with such issue, and to still remain in the cointegration environment, we introduce two new tests for asymmetry in the error-correction term – wave test and rescaled range ratio test.

---

long-term asymmetry is based on the null hypothesis  $H_0 : \beta^+ = \beta^-$  against the alternative  $H_1 : \beta^+ > \beta^-$  for the “rockets and feathers” effect.

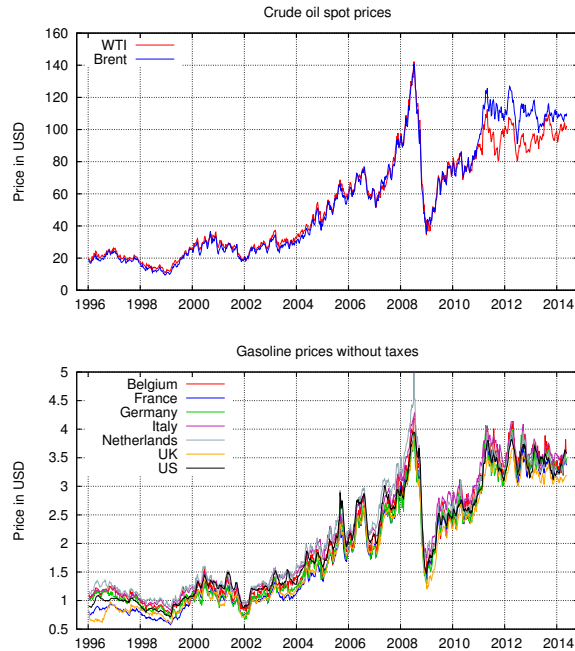
On the dataset of seven national gasoline price series, we find no statistically significant signs of the “rockets and feathers” effect. No price asymmetry was found, thus we suggest policy makers do not interfere. We did not identified any market failure, hence we believe there is no need for interventions. However, this does not necessarily discard the previous results showing asymmetry as we limit ourselves to the national data only. The results might indeed differ for more local price series.

Importantly, the proposed framework is not limited only to the gasoline-oil relationship but it can be utilized for any economic and financial series which are considered in the equilibrium cointegrated relationship and the adjustment rate might be asymmetric. The article can thus serve as a reference for future research in this area.

## **Acknowledgements**

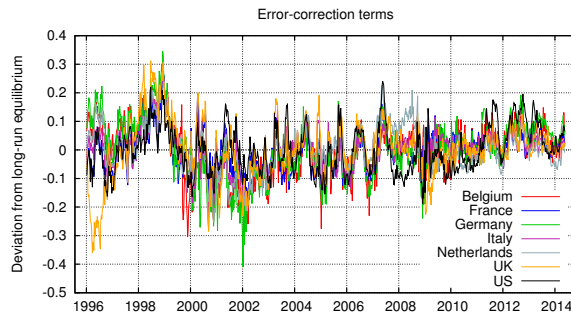
Support from the Czech Science Foundation under projects No. P402/11/0948 and No. 14-11402P is gratefully acknowledged.

Figure 3.1: Crude oil and gasoline prices



Crude oil prices (upper panel) for Brent and WTI are reported in the US dollars per barrel. Retail gasoline prices (lower panel) corrected for taxes are reported in the US dollars per gallon. All series have been obtained from [www.eia.gov](http://www.eia.gov).

Figure 3.2: Error-correction terms



Error-correction terms are obtained from the cointegration relationship between respective retail gasoline price and crude oil. Logarithmic relationship between the series is estimated based on Eq. 3.1.



Table 3.1: Summary of the “rockets and feathers” literature

Reference	Period	Country	Model/method	Results
Al-Gudhea <i>et al.</i> (2007)	1998–2004	USA	TAR, M-TAR, VECM	Asymmetry
Bachmeier & Griffin (2003)	1985–1998	USA	ECM (asymmetric)	Symmetry
Bacon (1991)	1982–1989	UK	Quadratic quantity adjustment function	Asymmetry
Balke <i>et al.</i> (1998)	1987–1996	USA	ECM (asymmetric)	Asymmetry
Balmaceda & Soruco (2008)	2001–2004	Santiago, Chile	ECM	Neutral
Bettendorf <i>et al.</i> (2003)	1996–2001	Netherlands	ECM (asymmetric)	Asymmetry
Borenstein & Shepard (2002)	1985–1995	USA	LAM, PAM and VAR	Asymmetry
Borenstein <i>et al.</i> (1997b)	1986–1992	USA	ECM	Asymmetry
Chen <i>et al.</i> (2005)	1991–2003	USA	ECM (threshold)	Asymmetry
Deltas (2008)	1988–2002	USA (separate states)	ECM (various)	Asymmetry
Douglas (2010)	1990–2008	USA	ECM	Depends on outliers
Duffy-Deno (1996)	1989–1993	Salt Lake City, USA	Markup model with first differences	Asymmetry
Eckert (2002)	1989–1994	Windsor, Ontario, Canada	ECM (reduced)	Asymmetry
Galeotti <i>et al.</i> (2003)	1985–2000	International (DE, ES, FR, IT, UK)	ECM (dynamic)	Asymmetry
Godby <i>et al.</i> (2000)	1990–1996	Canada (13 cities)	TAR within EC framework	Symmetry
Grasso & Manera (2007)	1985–2003	International (DE, ES, FR, IT, UK)	ECM (asymmetric, threshold)	Asymmetry
Honarvar (2009)	1981–2007	USA	ECM (crouching)	Asymmetry
Johnson (2002)	1996–1998	USA (15 cities)	ECM	Asymmetry
Karrenbrock (1991)	1983–1990	USA	Markup model with first differences	Symmetry
Kaufmann & Laskowski (2005)	1986–2002	USA	ECM (restricted and unrestricted)	Asymmetry
Lewis (2011)	2000–2001	San Diego, CA, USA	Consumer search model (with EC term)	Asymmetry
Liu <i>et al.</i> (2010)	2004–2009	New Zealand	ECM (asymmetric)	Asymmetry
Nagy Eltony (1998)	1980–1996	UK and USA	ECM (dynamic)	Asymmetry
Oladunjoye (2008)	1987–2004	USA	ECM (asymmetric)	Symmetry
Panagiotidis & Rutledge (2007)	1996–2003	UK	VECM	Symmetry
Radchenko (2005)	1993–2003	USA	ECM, VAR and PAM	Asymmetry
Reilly & Witt (1998)	1982–1995	UK	ECM (unrestricted dynamic)	Asymmetry
Tappata (2009)	Theoretical	General	Consumer search model	Asymmetry
Verlinda (2008)	2002–2003	USA	ECM	Asymmetry

Abbreviations: ECM (error-correction model), M-TAR (momentum threshold autoregressive model), PAM (partial adjustment model), LAM (lagged adjustment model), TAR (threshold autoregressive model), VAR (vector autoregression), VECM (vector error-correction model)

Table 3.2: Unit-root and stationarity testing

Country	ADF	<i>p</i> -value	KPSS	<i>p</i> -value
Belgium	-1.1166	> 0.1	10.9231	< 0.01
France	-1.1415	> 0.1	11.1559	< 0.01
Germany	-1.1823	> 0.1	10.8568	< 0.01
Italy	-0.9969	> 0.1	11.1836	< 0.01
Netherlands	-1.2177	> 0.1	10.6809	< 0.01
UK	-1.6644	> 0.1	10.9663	< 0.01
US	-0.8690	> 0.1	11.0235	< 0.01
Brent	-0.9535	> 0.1	11.0037	< 0.01
WTI	-1.1199	> 0.1	10.8473	< 0.01

Table 3.3: Cointegration & error-correction term testing

Country	Transmission	SE	ADF	p-value	KPSS	p-value	LWE	GPH
Belgium	0.6804	0.0123	-3.2763	0.0160	1.2094	< 0.01	0.6574 [0.0645]	0.6857 [0.0924]
France	0.7842	0.0096	-5.1817	< 0.01	0.7797	< 0.01	0.5201 [0.0645]	0.6012 [0.0982]
Germany	0.7005	0.0146	-3.7932	< 0.01	1.2647	< 0.01	0.7139 [0.0645]	0.8044 [0.1117]
Italy	0.6690	0.0104	-2.8726	0.0486	0.8037	< 0.01	0.6138 [0.0645]	0.6709 [0.1102]
Netherlands	0.6329	0.0114	-3.9637	< 0.01	0.5147	0.0420	0.7105 [0.0645]	0.7000 [0.1024]
UK	0.7478	0.0146	-4.0413	< 0.01	0.3121	> 0.1	0.6036 [0.0645]	0.5217 [0.0936]
US	0.7560	0.0106	-4.4462	< 0.01	0.6123	0.0290	0.4630 [0.0645]	0.4995 [0.1275]

Table 3.4: Asymmetry in error-correction term testing

Country	Wave test	<i>p</i> -value	RRR test	<i>p</i> -value	ECM test	<i>p</i> -value
Belgium	-2.5303	> 0.1	1.4876	> 0.1	2.0320	0.0211
France	-2.6220	> 0.1	1.0547	> 0.1	-0.1000	> 0.1
Germany	-4.4207	> 0.1	1.2883	> 0.1	2.0205	0.0217
Italy	-1.2520	> 0.1	1.2358	> 0.1	0.7598	> 0.1
Netherlands	-1.9005	> 0.1	0.9062	> 0.1	0.1585	> 0.1
UK	-0.8635	> 0.1	1.0037	> 0.1	-0.2975	> 0.1
US	-4.0140	> 0.1	0.7796	> 0.1	-1.5456	> 0.1

## Chapter 4

# The Merit Order Effect of Czech Photovoltaic Plants

**Published as:** Luňáčková Petra, Průša Jan and Janda Karel (2017): “The Merit Order Effect of Czech Photovoltaic Plants.” *Energy Policy* 106: pp. 138-147.

**Abstract:** We assess the impact of photovoltaic power plants on the electricity supply curve in the Czech Republic. The merit order effect is estimated as the elasticity of electricity spot price with respect to change in supply of electricity from renewable sources. Data for the Czech electricity spot market from 2010 to 2015 are analyzed as this is the period with the steepest increase in a renewable generation capacity. The effect is estimated separately for solar and other renewable sources. We find a significant difference between these two groups. Our results show that based on hourly, daily and weekly data energy produced by Czech solar power plants does not decrease electricity spot price, creating double cost to the end consumer. However, the merit order effect based on averaged daily and weekly data is shown to exist for other renewable sources excluding solar (mainly water and wind). This contributes to the conclusion that the Czech renewables policy that prefers solar to other renewable sources may be considered as suboptimal.

Keyword: energy subsidies, photovoltaic, renewables, merit order effect

*JEL codes: Q42, H23, M21*

## 4.1 Introduction

Photovoltaic power plants in the Czech Republic were subsidized as a part of the EU “20-20-20” energy strategy implementation. The combination of a very generous public support scheme and a significant photovoltaic technology price reduction led to a solar boom (Timilsina *et al.* 2012; Janda *et al.* 2014). Nowadays, in the Czech Republic there are four times more photovoltaic plants than wind plants (in terms of the MWh production, for details see Table 4.5), in spite of the fact that in other central European countries wind plants prevail. Before legislation reacted to the photovoltaic boom (by the end of 2010), the Czech installed solar capacity rose from 40 MW in 2008 to 1960 MW in 2010 (ERU 2015). The Czech subsidy for solar electricity dropped from initial 15,565 CZK/MWh (i.e. about 620 euros) in 2006 to zero for newly built commercial photovoltaic plants in 2014 (ERU 2013).

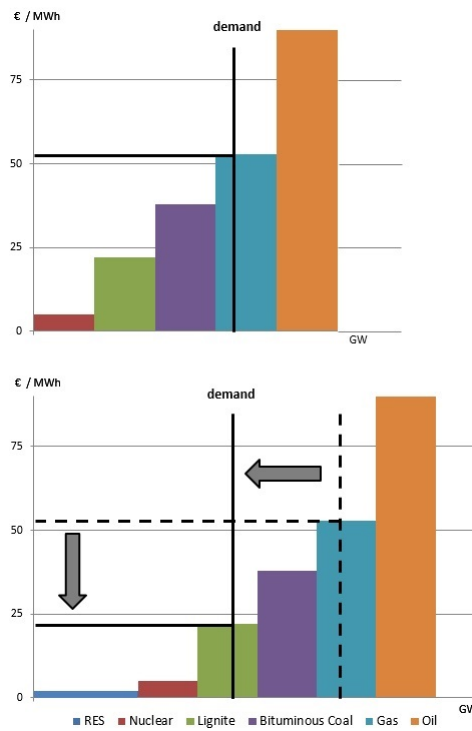
Progressively more ambitious goals of the Energy Strategy of the EU (2014) indicate the growing importance of energy sustainability and of renewable energy sources (RES) support. This paper contributes to the current merit order effect (MOE) discussion through the analysis of the Czech electricity market with the focus on renewable sources, in particular solar power plants.

The merit order effect of renewable energy sources stems from their almost zero short run marginal costs (SRMC) (given by the nature of sunlight, wind or water). Consider the merit order (supply) curve which ranks power plants according to their short run marginal costs. Because of very low SRMC, RES enter “first” (from the left) shifting the entire supply curve to the right. This shift of the supply curve to the right that happens when RES enter the market, *ceteris paribus*, causes price decrease. This is the mechanism of the merit order effect, for graphical illustration see Figure 4.1. Large amounts of renewable energy may push the marginal (price setting) plant out of the market and cause a price decrease. This effect is reinforced by fixed spot demand.

The exact marginal costs differ but there is some general merit order as illustrated by Figure 4.1, from the left to the right according to the typical SRMC: supported renewable sources – solar, wind, hydro –, baseload nuclear plants, lignite and coal (often marginal) and peaking gas and oil (marginal in case of no wind, no sun and high demand). Merit order curve is not “fixed” but in the short-run, it is usually fairly stable.

Given the specific Czech electricity market conditions, our analysis focuses on the photovoltaic power plants. In 2013 photovoltaic plants produced less

Figure 4.1: Merit order effect mechanism (illustrative scheme)



Illustrative scheme of merit order effect, without RES (upper) and price decrease with RES (lower)

than one quarter of the total volume of the supported energy sources in the Czech Republic but they received more than 60% of 37 billion CZK subsidies paid (OTE 2013) as shown in Figure 4.2. Current Czech RES production shares are quite surprising when compared to the predictions made before the solar boom. Back then Czech Republic expected the biomass to constitute about 80-85% of RES (Havlíčková *et al.* 2011).

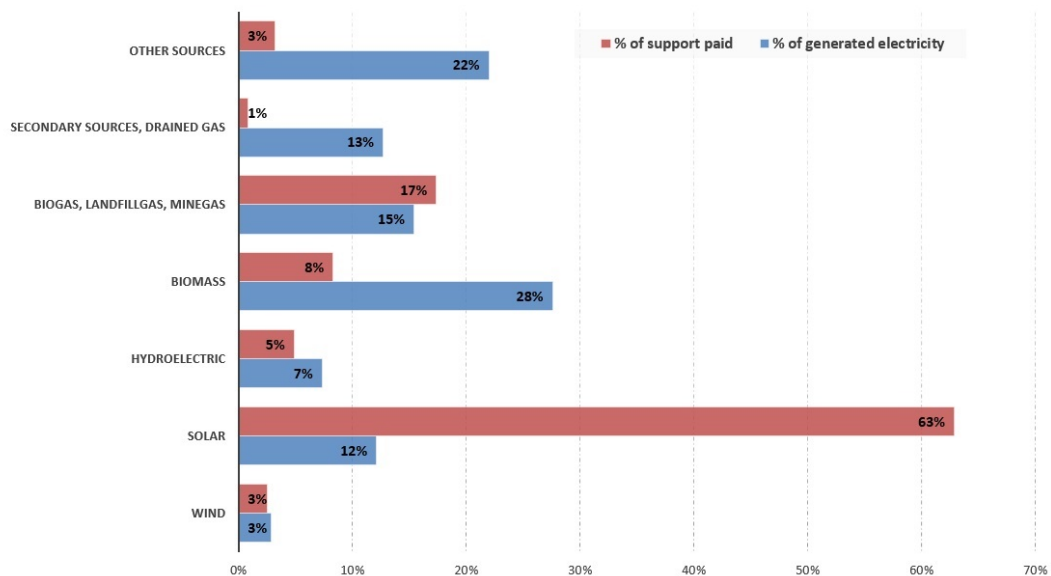
The MOE in theory decreases electricity wholesale price (i.e. it is negative) which benefits the consumers, yet at the same time, RES causing the MOE are financed through electricity surcharge and subsidies which are passed on the end consumers, causing additional costs to consumers. Thus, do benefits outweigh the costs? There are studies that claim that MOE offsets the cost of subsidies like Dillig *et al.* (2016) or McConnell *et al.* (2013), there are also studies like Clò *et al.* (2015) which distinguish between RES plants whose MOE counterbalances the costs of support (wind) and those that does not (solar) and finally there are studies such as Munksgaard & Morthorst (2008) that show that cost of subsidies are compensated by the MOE only to some extent. There is not a general agreement as the effect is always case specific reflecting market design, feed-in tariffs, rules and other conditions.

Our results suggest that not only is the overall Czech MOE fairly small, but in addition, it does not apply to all RES. Specifically, we find the relationship between electricity wholesale market spot price and photovoltaic production to be non negative (i.e. higher quantity does not lead to lower price). As a result, solar electricity creates a double cost to the end consumer — both through the subsidy and through the inverse merit order effect.

The rest of the paper is structured as follows. Section 4.2 introduces the Czech energy market and renewable sources policies. It is followed by Section 4.3 which focuses on the relevant literature. Section 4.4 describes the utilized dataset, followed by Section 4.5 on methodology. Section 4.6 presents the results, Section 4.7 provides further discussion of the results and Section 4.8 concludes.



Figure 4.2: Shares of volumes produced (in blue) and shares of support paid (in red) by type of RES and secondary sources, Czech Republic, 2013



Source: OTE Annual Report 2013

## 4.2 Czech Energy Market and Renewable Sources Policies

### 4.2.1 Market Design

The Czech electricity market is characterized by a very positive attitude towards nuclear power (Keller *et al.* 2012), by a dominant position of brown coal in the Czech electricity generation (Bejbl *et al.* 2014; Recka & Scasny 2016) and by a strong role of electricity export since the Czech Republic ranks sixth in the world and fourth in Europe in electricity exports (Sivek *et al.* 2012b). For the amount of Czech electricity export and its share on consumption see Table 4.1. In the long run Czech electricity demand is expected to grow slowly (CEPS 2015b) but given that the country is a net exporter the reserve margin is significant, see also Table 4.2 on installed capacity and actual production.

The difference between installed capacity and production is significant, however, better way of describing the available capacity overhang is through Figure 4.3 which pictures the expected overall Czech available power in 2015 as the sum of the necessary reserves, national load (gross consumption) and what “re-

mains” can be perceived as possible trade opportunity. Figure 4.4 displays the excess supply i.e. what remains when national load and necessary reserves are covered. The expected total available production includes all planned outages and maintenance and it is based on detailed information from individual generators provided to the Czech Electricity Transmission System (CEPS 2015b).

Full liberalization of the Czech electricity market was reached in 2006. Since then generation, transmission and distribution are vertically unbundled and consumers are free to choose their supplier. Transmission and distribution are regulated (due to their network nature), generators and suppliers operate in free market. Electricity produced by the generators is traded in electricity wholesale market (KU Leuven Energy Institute 2015). Czech electricity market is energy-only market, which means that utility companies are paid for generated electricity, as opposed to the capacity market design used elsewhere under which the utility companies would be paid for maintaining reserve capacity.

Similarly to a majority of the European electricity markets Czech electricity market employs a price based approach which motivates generation up to the point where SRMC and price of an extra MWh of electricity are equal (Cramton *et al.* 2013). This in combination with quite inflexible demand contributes to significant price volatility and variability during a day/week/season. In order to avoid scarcity or even electricity blackouts, there is a system of markets which insures that electricity supply and demand are always in equilibrium.

Majority of the Czech electricity demand is covered by over-the-counter trading contracts (around 70% (OTE 2015b)). These contracts are settled before the actual delivery, without knowing the exact amount of electricity needed at the moment of delivery. A day before the delivery suppliers correct their portfolio in day ahead market and on the delivery day they correct it in the intra-day market. The remaining mismatch between supply and demand is covered by the balancing market where positive and negative imbalances of various participants are matched and resulting system imbalance is covered by the reserves of the Czech Electricity Transmission System (CEPS). Market participants are charged for their imbalances which motivates them to be balance responsible (OTE 2015b).

As opposed to US or Australian “gross pool” approach to system balancing which ignores the bilateral contracts signed by system users and traders, the Czech system uses “net pool” approach which measures imbalances as the difference between a system participant’s net contract position and his net physical output. Net contract position is given as sales minus purchases while

net physical output is computed as production minus consumption. The difference between contract and physical position is recorded as an imbalance. This imbalance is settled at a price which is determined not by a market, but by a set of rules included in the compulsory balancing and settlement agreement.

In the Czech system the subjects of settlement are rewarded or penalized according to the type of their own imbalance. If a subject of settlement helps to bring the grid to stability, it is rewarded for it. However, if its imbalance has the same direction as the overall one, it has to pay a penalty. Czech electricity and gas market operator (OTE) defines market participants, who are responsible for their own imbalance as subjects of settlement. Not every electricity producer or consumer is a clearance subject. However, every production or consumption has to be assigned to a clearance subject. As of June 2015 OTE registers around 100 subjects. These are mostly energy trading companies, big producers or big customers. Czech households are not subjects of settlement but their responsibility is taken over by their supplier. Further details of Czech electricity balancing system and a quantitative estimation of the impact of solar production on Czech electricity grid system imbalance is provided by Janda & Tuma (2016).

The central market of Czech electricity system is the day ahead market, which is organized since 2002. This market is crucial also for our analysis as we work with price set at this market. The day ahead price serves as a reference price also for other markets such as for futures or for bilateral contracts.

The Czech day ahead “spot” electricity market is coupled with the Slovak, Hungarian and Romanian markets. Romania has been included since November 2014 as the latest partner (OTE 2014). “Market Coupling trading means that bids for purchase or sale of electricity for the following day are matched jointly even from neighboring market places without the need to acquire transmission capacity, up to the level of of transmission capacity reserved for market coupling” (OTE 2015b, p. 7) . Moreover, Czech market is naturally interconnected with the German market through electricity flows and export, which influences Czech electricity market spot prices. Detailed description of electricity transmission network in Central Europe with focus on Germany and Czech Republic is provided by Janda *et al.* (2016).

### 4.2.2 Renewable Sources Policies

Similarly to other EU countries, the Czech renewable sources policies are driven mainly by climate change concerns, especially by efforts to reduce greenhouse gas emissions and its associated social costs (Havranek *et al.* 2015). Besides the renewable electricity generation, which is the subject of this article, significant attention is paid to energy efficiency (Karasek & Pavlica 2016) and to bioenergy. The wind and solar energy are fundamentally new energy resources with new economic policy constituency and issues (Torani *et al.* 2016).

Czech geographic conditions allow the installation of renewable energy plants which make use of weather, like wind or sun, however, due to the natural environment these types of plants yield only average results. The Czech solar policy had no foundations in intensity or hours of sunshine (Šúri *et al.* 2007). While photovoltaic energy is in general a subset of solar energy, there is no concentrating solar power (CSP) project in the Czech Republic (NREL 2015) thus for us both terms are interchangeable and Czech solar means photovoltaic.

The EU indicative target for 2010 for the Czech Republic was set to 8% share of RES on consumption (Act 2005) (to 13% for 2020 (Act 2012)). In order to reach it, the government enacted economic incentives for renewable energy sources, which were supposed to motivate investment into RES, by passing the Act on Promotion of Electricity Produced from Renewable Energy Sources No.180/ 2005 Coll. (Act 2005). Since then there is an explicit priority dispatch for all RES generation in the Czech Republic set in the law (Act 2012), according to which every MWh of green electricity produced has to be paid a guaranteed (subsidized) price, based on the year the respective generation capacity was put in operation.

The renewable energy sources are not competitive on their own (especially not the Czech solar plants as shown by Prusa *et al.* (2013)) so the support was very generous and fixed for every MWh of the green energy produced and supplied to the grid. As stated in Section 4.1, munificent support scheme together with photovoltaic technology price decrease gave rise to a boom.

The logic of the support scheme was changed in consequence of the solar boom. First, amendment of the (Act 2005) introduced a solar tax of 26% for the period of 2011-2013 for solar plants with installed capacity over 30kW and launched in the boom years (2009-2010). Second, (Act 2005) was replaced by the Czech legal Act No. 165/2012 Coll., on Supported Energy Sources. Third, amendment of (Act 2012) extended the solar tax period, the tax remained valid

Table 4.1: Czech Electricity Production, Consumption and Export 2010-2015

Electricity in GWh	2010	2011	2012	2013	2014	2015
Gross production	85 910	87 561	87 574	87 065	86 003	83 888
Gross consumption	70 962	70 517	70 453	70 177	69 622	71 014
Export	14 948	17 044	17 120	16 887	16 300	12 516
Share of Export on Consumption	21%	24%	24%	24%	23%	18%

Source: ERU Annual Report on the Operation of the Energy System in the Czech Republic in 2015

for plants launched in the great boom year 2010 and in the amount of 10% it is to be paid till the end of their technical lifetime (20 years). Support for solar plants was significantly cut and cancelled for all solar plants launched after 2013, see Table 4.4. Due to the solar boom, national target of 13% share of RES on Czech gross final energy consumption planned for 2020 was reached already in 2013, see Table 4.7.

Intense support in combination with solar boom created financial burden which was passed on consumers. Consequently the retail surcharge increased tenfold between 2009 and 2013, see Table 4.3. Fixed guaranteed price (feed-in tariff) was the sum of market price and subsidy, so with the electricity spot market price falling in 2011-2013 (OTE 2015b) the surcharge was rising and since 2011 the subsidies were financed also through state budget (enacted by the amendment of Act (2005)).

Even though the support was cut, because of the previously launched plants with guaranteed price, the costs will remain high. Theory suggests that renewables could decrease wholesale price through MOE (and increased supply) and counterbalance the costs of subsidies to some extent. However, our research clearly shows that this does not hold in the Czech Republic because solar plants cause no MOE there and the MOE of other renewable plants is negligible compared to the subsidies.

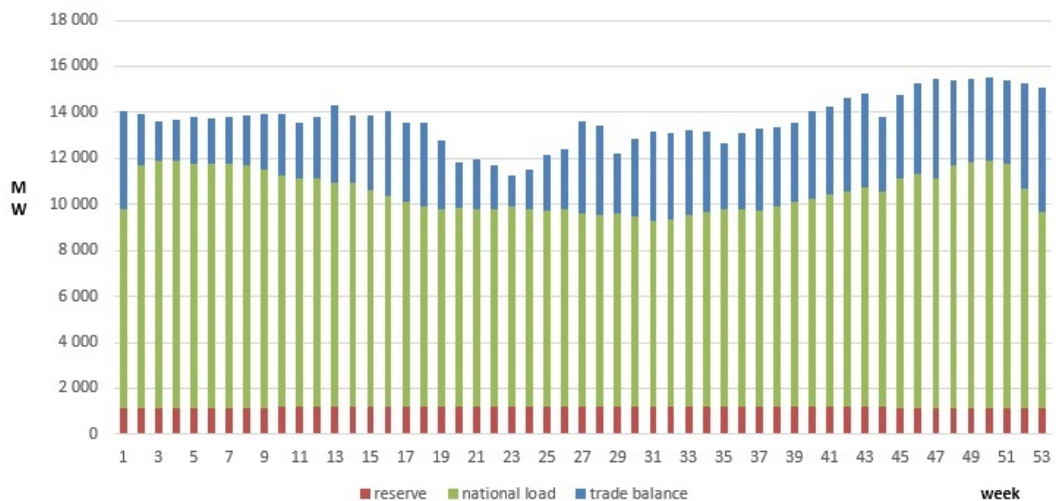
The case of the Czech solar power policy is a story of enormous costs, huge subsidies and even bigger scandals. It is a good example of how market principles can be misunderstood by political leaders (Smrčka 2011). The EU strategy demanding growing share of energy to come from renewable sources was simply adopted with neither public discussion nor cost analysis (Sivek *et al.*

Table 4.2: Czech 2015 Electricity Production and Installed Capacity

2015	Production (GWh)	Installed capacity (MW)	Installed capacity share (%)
Nuclear	26 840.8	4 290.0	20
Steam	44 816.5	10 737.9	49
Combined cycle gas	2 749.0	1 363.3	6
Gas and combustion	3 574.7	859.9	4
Water	1 794.8	1 087.5	5
Pumped storage	1 276.0	1 171.5	5
Wind	572.6	280.6	1
Photovoltaic	2 263.8	2 074.9	10
<b>TOTAL</b>	<b>83 888.2</b>	<b>21 865.6</b>	<b>100</b>

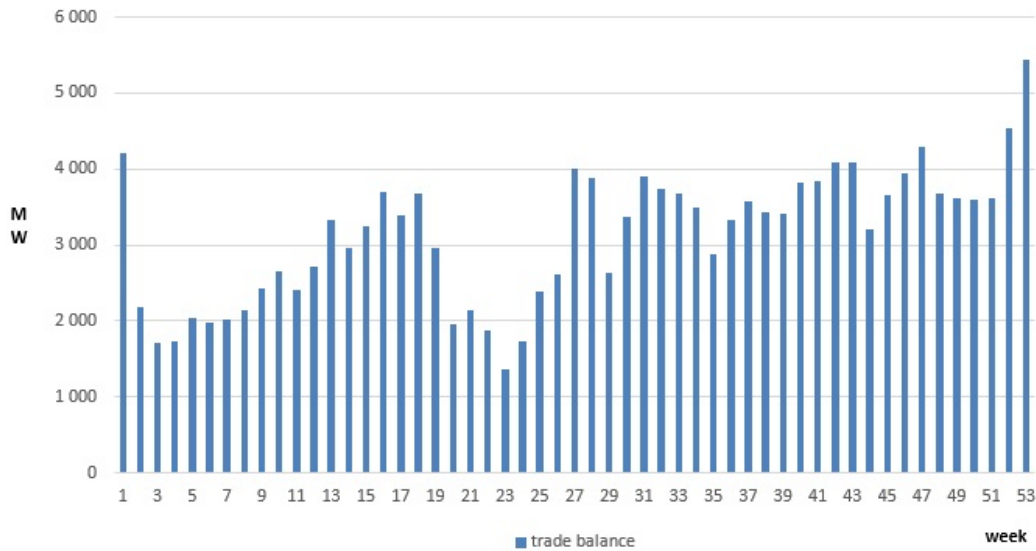
Source: ERU Annual Report on the Operation of the Energy System in the Czech Republic in 2015

Figure 4.3: Czech Electricity Power Balance, 2015



Source: CEPS Preparation of Annual Operation 2015

Figure 4.4: Power Balance - Resulting Possible Trade Opportunity, 2015



Source: CEPS Preparation of Annual Operation 2015

Table 4.3: Czech RES Financing 2009-2015

Year	2009	2010	2011	2012	2013	2014	2015
Consumer RES surcharge per MWh (CZK)	52	166	370	419	583	495	495
State budget RES subsidy (billion CZK)	0	0	11.7	11.7	11.7	15.7	15.7
Solar tax since 2011 (%)	0	0	26	26	26	10	10
Support paid (billion CZK)	3	9	32	35	37	41	44

Note: Solar tax was applied based on the launch year, given rates apply to 2010 launch year. Consumer surcharge in 2015 formed approximately 15% of the electricity price (without taxes) charged to consumers (ERU 2014).

Source: Ministry of Industry and Trade, Energy Regulatory Office and Czech Electricity and Gas Market Operator

Table 4.4: Czech Solar Feed-in Tariffs 2005-2014, in CZK

Based on the launch year	Feed-in tariffs in CZK, solar plants > 30kW
2005	7 418
2006	15 565
2007	15 565
2008	15 180
2009	14 139
2010	13 161
2011	5 837 - 6 264
2012	0
2013	0
2014	0

Source: Price Decision of the Energy Regulatory Office no. 4/2013 dated 27.11.2013

2012a). The mismatch between a guaranteed price of 620 euros (ERU 2013) and a market price around 30-40 euros at the time, was highly beneficial for the solar power producers.

When the conditions of the solar plants' support were about to be changed (since January 1st, 2011) there was a fierce chase for the launch of the plants under the "old" favorable terms. Investors wanted to be eligible for higher support and focused on the launch day stamp, sometime through illegal practices. Consequently there was a significant number (and production volume) of photovoltaic plants which were officially listed as in operation by December 31st, 2010, however, they were fully finished and started to produce only several months later during 2011 (CTK 2014). While these frauds, scandals and law-breaking cases may compromise the validity of photovoltaic capacity data for the year 2010, they do not influence the actual production data reported in our Table 4.5 and the data used in our empirical analysis.

### 4.3 Literature Review

While the studies dealing with RES differ in methods, data (both frequency and source) and objectives, their general conclusion is similar – renewable electricity has a tendency to reduce the wholesale prices on the spot market via the merit



Table 4.5: Production of Czech power plants 2001-2015, in GWh

Year	Steam	Nuclear	Gas	Water	Solar	Wind	Total (GWh)
2001	55 114.3	14 749.3	2 316.0	2 467.4	<b>0.0</b>	0.2	74 647.2
2002	52 409.8	18 738.2	2 352.9	2 845.5	<b>0.0</b>	1.6	76 348.0
2003	53 045.6	25 871.9	2 511.0	1 794.2	<b>0.0</b>	3.9	83 226.6
2004	52 811.0	26 324.7	2 624.6	2 562.8	<b>0.1</b>	9.9	84 333.1
2005	52 137.2	24 727.6	2 665.4	3 027.0	<b>0.1</b>	21.3	82 578.6
2006	52 395.4	26 046.5	2 612.1	3 257.3	<b>0.2</b>	49.4	84 360.9
2007	56 728.2	26 172.1	2 472.9	2 523.7	<b>1.8</b>	125.1	88 023.8
2008	51 218.8	26 551.0	3 112.7	2 376.3	<b>12.9</b>	244.7	83 516.4
2009	48 457.4	27 207.8	3 225.2	2 982.7	<b>88.8</b>	288.1	82 250.0
2010	49 979.7	27 988.2	3 600.4	3 380.6	<b>615.7</b>	335.5	85 900.1
2011	49 973.0	28 282.6	3 955.1	2 835.0	<b>2 118.0</b>	396.8	87 560.6
2012	47 261.0	30 324.2	4 435.1	2 963.0	<b>2 173.1</b>	417.3	87 573.7
2013	44 737.0	30 745.3	5 272.4	3 761.7	<b>2 070.2</b>	478.3	87 064.9
2014	44 419.3	30 324.9	5 699.1	2 960.7	<b>2 122.9</b>	476.5	86 003.4
2015	44 816.5	26 840.8	6 323.7	3 070.8	<b>2 263.8</b>	572.6	83 888.3

Source: ERU Annual Report on the Operation of the Energy System in the Czech Republic in 2015

order effect. The impact of MOE is greater when the system approaches its capacity limits. Since the different results reported in the literature may be influenced by the choice of data frequency used for the estimation of MOE, in our paper we compare the results obtained both with original hourly data and with their daily and weekly averages.

The influence of wind on electricity prices is an issue mainly in Germany, Spain, Australia and Denmark, where the wind penetration is high. In general, the number of wind analyses exceeds the solar studies by far. However, due to the specific situation on the Czech electricity market described above in detail, we focus on the solar side of the production. Table 4.5 provides a detailed structure of the Czech electricity production between years 2001 and 2015.

Tveten *et al.* (2013) study the solar feed-in tariffs (2009-2011) and the MOE in Germany. They develop a model to predict electricity prices in Germany with and without solar electricity production. Their results show that the daily price volatility has decreased and average electricity prices have fallen by 7%. We test whether there is a similar effect present in the Czech market.

Mulder & Scholtens (2013) investigate a suspected increased sensitivity of electricity spot prices to weather conditions, in the Netherlands between 2006

and 2011, taking into account the situation in Germany as well, due to the interconnection of the markets (there is a similar interconnection between the Czech and German electricity markets). With the use of daily price averages, they conclude that the German wind negatively affects Dutch electricity spot prices. However, they do not find any similar effect in the case of sunshine intensity.

Keles *et al.* (2013) simulate wind data using an autoregressive approach. They estimate the MOE on the German data for years 2006-2009, obtaining results showing that electricity price drops by 1.47 EUR/MWh per additional GWh produced by RES. Also Würzburg *et al.* (2013) aim at determining the size of the MOE in the Austrian-German region. Their multivariate regression model using prices in form of daily averages estimates the MOE to be 2%. Based on data between VII/2010 and VI/2012 they show that electricity price drops by 1 EUR/MWh per additional GWh produced by RES.

Sensfuss *et al.* (2008) analyze the price effect of RES on German spot market in detail. Their results are based on simulations and they show a considerable price reduction. Their calculations indicate that the price was on average lower by 7,83 EUR/MWh due to RES in 2006. They suggest that the MOE may exceed the net support payments. Other German authors such as Dillig *et al.* (2016) go even further and claim that had there been no RES, not only would electricity have cost more but the system would have even been on the verge of shortages.

Unlike others, McConnell *et al.* (2013) focus on photovoltaic plants and they model the MOE in Australian National Electricity Market retrospectively. According to the authors, the overall effect has been desirable – the system favors the consumers in the financial terms. They show that in 1% of the time, during high wind, electricity prices were even negative. Clò *et al.* (2015) analyze the Italian market, concluding that there is a solar merit order effect reducing Italian wholesale prices by the minimum of 2.3 euros per MWh for every GWh increase (2005-2013). They find the wind MOE to be even stronger – 4.2 euros per MWh for every GWh increase.

Moreno *et al.* (2012) take into account another factor – a degree of competition – and they are among the few whose results suggest that with the deployment of RES, the electricity prices increase by a small amount. Their empirical analysis of panel data from Eurostat (EU27, 1998-2009) shows that RES need not be beneficial. Possible increase of the average electricity market price due to implementation of photovoltaics is suggested also by Milstein &

Tishler (2011).

Our brief literature review, supported also by current study by Welisch *et al.* (2016), indicates that most authors have found the presence of merit order effect, i.e. that RES decrease electricity wholesale prices. The literature also acknowledges the costs RES impose on the entire system. High volatility/variability puts reserves and balancing capacity under costly pressure, where under high wind RES overload the transmission system causing extra costs (Vrba *et al.* 2015). Also, RES negatively affect investment into other technologies, mainly by contributing to a generally high uncertainty of future prospects of energy markets. Critics also perceive the RES support as a regressive form of taxation (McConnell *et al.* 2013).

The literature on the Czech electricity market is very limited. Besides the study of Křišťoufek & Luňáčková (2013), who analyze properties of hourly prices of electricity in the Czech Republic, the Czech data has only been viewed as a part of the EU or the Central European region datasets. To the best of our knowledge, there is no published journal article on the Czech merit order effect. Therefore, we contribute to its analysis and to the investigation of the MOE behavior in general. Our results in this paper highlight the sensitivity of MOE estimations to frequency (hourly, daily or weekly) of the data used in the empirical work and to suitable geographic conditions.

## 4.4 Data

The electricity spot market price in the Czech Republic, which is our variable of interest, is quoted in euros and thus it is not influenced by the exchange rate conversion or connected risk factors. It is widely accepted as reference price for electricity in both literature and trading. The effect of market coupling on the spot price is limited by the cross border infrastructure. The effect of export on the spot price is also limited, given that majority of the export is covered by bilateral contracts.

In our analysis, we use publicly available data. We employ hourly spot price in EUR/MWh from OTE (Czech electricity and gas market operator) and generation in MWh from CEPS (Czech Electricity Transmission System). Specifically, we use detailed hourly total gross electricity generation within the Czech power system according to the individual power plant types – thermal, combined-cycle gas turbine, nuclear, hydro, pumped-storage, alternative, photovoltaic and wind power plant. Production data represent our explanatory

Table 4.6: Summary of utilized variables, in MWh, 50 371 observations

Variable	Mean	Std.Dev.
Solar	197.4	350.4
Total production	9546.0	1318.8
Price (EUR/MWh)	40.0	16.1
Conventional	8201.5	1227.3
RES	1344.4	472.8
RES without solar	1147.0	369.5

variables. Table 4.6 summarizes the basic characteristics of the analyzed variables. Throughout the paper, price always refers to the electricity wholesale day ahead (spot) market price and generation means the entire Czech production (i.e. the sum of demand and export).

The dataset covers period from January 2010 to September 2015. This five-year period has seen a historic development of solar generation in the Czech Republic, including the boom. While in 2009, the solar generation was simply insignificant (its share in renewables was below 2% and only 0.13% in the total consumption), in 2010 the upward tendency began at 10% share in renewables reaching 30% share in 2011 (ERU 2015), see Table 4.7.

Given that there is a general agreement in the literature that for electricity production, consumption and pricing intra-day timing (the location of consumption and production peaks and troughs) matter, we first compute the MOE based on hourly data. Since some literature provides MOE estimates based on lower frequency data, we subsequently also provide a robustness check of our results by performing the regression analysis with daily and weekly averages. Such analysis (MOE on averaged data) was done by Würzburg *et al.* (2013) on German daily averages or by Gelabert *et al.* (2011) on Spanish data.

The rationale for using averaged data follows: under the energy-only market regime (which is the case of the Czech Republic) electricity prices on the day ahead (spot) market are extremely volatile, the volatility feature could actually interfere with the results, and therefore averaging limits the influence of the volatility on the results.

Volatility is typical for electricity generation in general but solar is regularly zero most of the day, increasing the volatility impact further. Such characteristic in fact goes against the standard assumption of the regression analysis

Table 4.7: Share of photovoltaics in renewables and total consumption 2006 - 2015, in MWh

Year	Photovoltaics production	RES total	Consumption gross	RES share on cons.(%)	Photovol. share on RES (%)
2006	170	3 512 650	71 729 500	4.90	0
2007	1 754	3 393 509	72 045 200	4.71	0.05
2008	12 937	3 738 459	72 049 267	5.19	0.35
2009	88 807	4 668 514	68 600 000	6.81	1.90
2010	615 702	5 886 915	70 961 700	8.30	10.46
2011	2 182 018	7 247 504	70 516 541	10.28	30.11
2012	2 148 624	8 055 026	70 453 278	11.43	26.67
2013	2 032 654	9 243 382	70 177 356	13.17	21.99
2014	2 122 869	9 169 709	69 622 096	13.17	23.15
2015	2 263 846	9 422 950	71 014 254	13.27	24.02

Source : ERU Annual Report on the Operation of the Energy System in the Czech Republic in 2015

which assumes the independent variables to have finite second moment, or in other words, an invertible design matrix. Even though the hourly solar data does not violate this assumption directly, it increases the variance of estimators considerably. Regardless the frequency of input data, our main conclusion remains qualitatively without any substantial change.

Electricity consumption is weather and temperature dependent and follows strong seasonal patterns (daily, weekly, yearly) (Lucia & Schwartz 2002) which means that production of this non-storable commodity needs to follow the same patterns. Wind and solar power plants, intermittent sources, are totally weather dependent and non-dispatchable. Production of solar power plants is usually easier to accommodate as it is supplementary to peak hours, since the hours of sunshine correspond to the hours of high electricity consumption. Wind does not match the peak demand and it may oversupply the market causing negative prices peaking even at  $-100$  EUR/MWh as reported by Nicolosi & Fürsch (2009). Contrary to RES, conventional sources like baseload nuclear plants, or coal and gas power plants are dispatchable but not truly flexible (Sovacool 2009). Our dataset reflects the above-described characteristics, thus we expect to run into autocorrelation, non-stationarity and endogeneity problems.

Our analysis consists of four steps. First, we build the fundamental regression equation where we regress price on conventional production and renewable

sources, and solve the related problems such as autocorrelation or endogeneity. Second, we split the renewable sources into photovoltaic and other RES, to quantify the MOE of photovoltaic plants. Third, we run our regression on hourly data and fourth, we perform the same analysis on daily and weekly data.

## 4.5 Methodology

Our model belongs to the class of parsimonious fundamental models which describe the basic relationship between production and price (Weron 2014). The purpose is to understand the effect of renewable sources on the power price and to quantify this merit order effect. Schematically, we aim to decompose

$$P = P_c + M, \quad (4.1)$$

where  $P$  is the observed market electricity price,  $P_c$  is the projected price without the supply of renewable sources (with conventional sources only,  $c$  stands for conventional) and  $M$  is the merit order effect of renewable sources. However,  $P_c$  is unknown so that we cannot make use of the above split. Instead, we estimate the linear regression model

$$p = \alpha + \beta_c q_c + \beta_r q_r + \epsilon, \quad (4.2)$$

where  $\epsilon$  is the error term,  $r$  stands for renewables, and price  $p$  as well as generation  $q$  are taken in logs to enhance interpretability. Given the variables in logarithmic forms, the MOE, represented by the  $\beta_r$  coefficient, could be defined as the elasticity of electricity wholesale spot price with respect to change in supply of electricity from renewable sources:

$$\beta_r = \frac{dP/P}{dQ_r/Q_r}. \quad (4.3)$$

Physical characteristics of electricity suggest that our time series is not stationary. Stationarity, broadly said, means that the series is mean-reverting, without periodic fluctuations or trends. However, electricity clearly shows seasonal fluctuations. We employ the Dickey-Fuller test (Dickey & Fuller 1979) with a linear time trend for testing the non-stationarity. We further define a vector of dummy variables for months of the year (11 dummy variables), days of the week (6), years (5) and Czech national holidays (11).

Time series typically suffer from autocorrelated residuals. This is valid

for the power time series even more strongly. For this purpose, we utilize the Durbin-Watson test (Durbin & Watson 1971). As the residuals in fact suffer from strong serial correlation, we correct for it using the Prais-Winsten methodology (Prais & Winsten 1954) which gives us estimates which are in addition robust to heteroscedasticity.

One of the crucial assumptions of the ordinary least squares regression to be unbiased and consistent is the mean independence of disturbances. One of the possible ways of interpreting such assumption is that the dependent (response) variable depends on independent (impulse) variables, and not vice versa. If the opposite holds, one has to solve the endogeneity problem. A classic cause of endogeneity is an uncontrolled for variable that influences both explanatory and explained variables. In our case, e.g. the dispatching rule might be the cause (see Clò *et al.* (2015) for a detailed discussion). One of the feasible methods to overcome the endogeneity problem is via the instrumental variables (IV) estimation.

On the one hand, we assume that  $q_r$  is given exogenously, both in the long run and in the short run. Long term supply in the Czech electricity market was driven mainly by subsidies defined by the law. Short term supply is driven by exogenous weather conditions (temperature, cloud cover, wind speed, etc.). On the other hand, supply of the conventional sources  $q_c$  is endogenous and correlated with the observed price  $p$ . As a valid instrument, we consider the total production  $Q$  ( $q$  in logs), which is by definition highly correlated with the production of conventional sources, but less so with  $p$ . The reason for lower correlation of  $p$  and  $q$  is that  $q$  contains exogenous components, such as  $q_r$ , planned outages, exports and available transmission capacities. Moreover, electricity demand is not motivated by a changing spot price as households have long-term contracts and consume electricity without any regard for pricing on the wholesale market. As we have found our instrument, we regress  $q_c$  on  $q$  in the first stage and in the second stage, we use the fitted values  $\hat{q}_c$  for the estimation of MOE.

Building on the just developed approach, we add dummy variables and simple time trend to Equation 4.2, employ Prais-Winsten methodology and instrumental variables to estimate our model and to obtain the MOE. First, we look for the overall MOE:

$$p = \alpha + \beta_c \hat{q}_c + \beta_r q_r + time + dummies + \epsilon, \quad (4.4)$$

where  $\hat{q}_c$  is obtained from the instrumental variable regression using the overall production. Our data contains not just the sum of RES production but figures for every type of green generation so that we can easily run the regression on the two types of renewables – “solar” and “others” – and estimate the solar MOE and MOE of other RES excluding solar, i.e

$$p = \alpha + \beta_c \hat{q}_c + \beta_s q_s + \beta_o q_o + time + dummies + \epsilon, \quad (4.5)$$

where  $s$  stands for the solar,  $o$  for the other renewable sources and  $c$  for the conventional production.

## 4.6 Results

We first estimate Equation 4.4 without instruments on hourly data using the autocorrelation adjustment by Prais-Winsten. The Durbin-Watson (DW) statistic of 0.40 indicates autocorrelation, while the transformed statistic of 1.88 indicates a strong improvement. We follow by estimating the Equation 4.5 using the total production instrument. The null hypothesis of under-identification (that the instrument is not correlated with the instrumented  $q_c$ ) is rejected even at 1% level. Similarly, the null hypothesis of weak identification (that the instrument is only weakly correlated with the instrumented  $q_c$ ) is rejected even at 1% level.

The results are reported in Table 4.8, and show non-negative merit order effects both for solar with  $\hat{\beta}_s = 0.003$  and other renewable sources with  $\hat{\beta}_o = 0.08$ . In particular MOE of solar plants is not statistically significantly different from zero ( $p$ -value = 0.224). In order to avoid over-specification of the model we dropped yearly dummies as not all of them were statistically significant and worked with dummies for hours, holidays, days and months. Dummies coefficients in Table 4.8 are skipped for the sake of brevity.

Reported results suggest that high volatility of solar production could have influenced the results. Therefore, it suggests that the model should be developed further, so we proceed with averaged data analysis to perform a check and get easily comparable results.

Electricity consumption, and hence also production, has a specific daily profile, see Figure 4.5 example, which reflects weather as well as working day habits (commercial demand during the day, rise of residential demand in the morning and evening). Energy Regulatory Office publishes consumption pro-



Table 4.8: Results of IV Regression, hourly data

	Coefficient	<i>p</i> -value
$\alpha$	-3.3555	< 0.01
$\widehat{\beta}_c$	1.2495	< 0.01
$\widehat{\beta}_s$	0.0029	0.224
$\widehat{\beta}_o$	0.0811	< 0.01
Time	$-3.1 \times 10^{-12}$	< 0.01
Holiday	-0.3807	< 0.01
Hourly dummies		all < 0.01
Daily dummies		all < 0.01
Monthly dummies		all < 0.01
Obs.	31 296	
$\bar{R}^2$	0.3776	

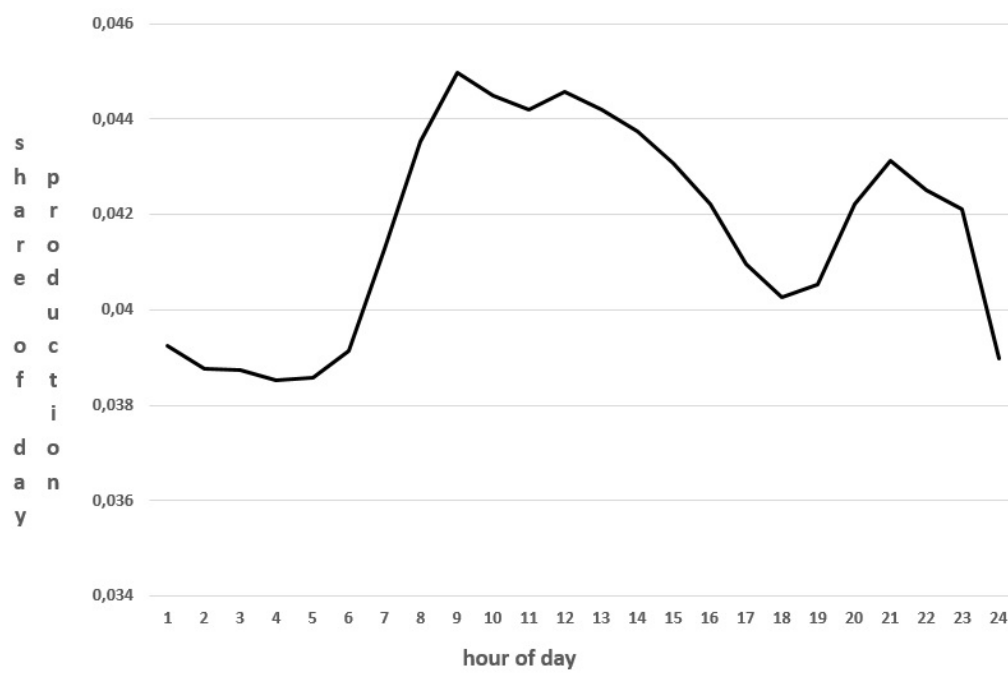
files for every month based on previous years' data and weather. So there is no typical profile representative of every single day thus, data cannot be averaged using only one set of weights. Every hour of production is a share of total daily production, thus we weigh each hour of the day by its share on that day production, i.e.

$$\text{weighted daily average of variable } a = \sum_{i=1}^{24} a_{h_i} \cdot \frac{\text{production } h_i}{\text{day production}},$$

where  $h_i$  is the  $i$ -th hour of the day. The weekly average is then a plain average of daily data.

The results of the regression on daily data are reported in Table 4.9 and confirm the above: merit order effect of solar appears non-negative. Statistically insignificant monthly dummies were dropped to avoid over-specification. Based on daily data regression there is a MOE present in the Czech electricity market but it is not global, meaning that not all renewable sources contribute to the merit order effect. Our results clearly show that the MOE of solar plants is non-negative, actually it has small positive effect on price, thus solars are not decreasing the price as expected. Other renewable sources are found to cause the MOE. With their production increasing, the electricity spot price decreases. Specifically, a 10% increase in production of other renewable sources results in a 2.2% price decrease.

Figure 4.5: Production Profile Example, Czech Republic, April 17th, 2014



Source: CEPS Generation Data

Table 4.9: Results of IV Regression, daily data

	Coefficient	<i>p</i> -value
$\alpha$	-3.7543	0.0264
$\hat{\beta}_c$	0.6031	< 0.01
$\hat{\beta}_s$	0.0716	< 0.01
$\hat{\beta}_o$	-0.2154	< 0.01
Time	0.0002	0.025
Holiday	-0.5664	< 0.01
Day2	0.0803	< 0.01
Day3	0.0907	< 0.01
Day4	0.0824	< 0.01
Day5	0.0551	0.0580
Day6	-0.0899	< 0.01
Day7	-0.4764	< 0.01
Year2011	-0.0172	0.6851
Year2012	-0.2998	< 0.01
Year2013	-0.5323	< 0.01
Year2014	-0.7077	< 0.01
Year2015	-1.0176	< 0.01
Obs.	2100	
$\bar{R}^2$	0.4392	

Table 4.10: Results of IV Regression, weekly data

	Coefficient	<i>p</i> -value
$\alpha$	9.9761	< 0.01
$\widehat{\beta}_c$	0.4435	< 0.01
$\widehat{\beta}_s$	0.0667	< 0.01
$\widehat{\beta}_o$	-0.2554	< 0.01
Year2011	0.4206	0.3054
Year2012	-1.0900	< 0.01
Year2013	-2.2573	< 0.01
Year2014	-3.0349	< 0.01
Year2015	-5.0653	< 0.01
Obs.	300	
$\bar{R}^2$	0.5030	

Our daily model explains 44% of the price variability (measured by adjusted R-squared) and all variables are statistically significant with the exception of the dummy variable for the year 2011. Moreover, the individual years effect corresponds to the fact that the wholesale price of electricity has been decreasing in recent years.

When we run the regression on weekly data, the results based on daily data are confirmed, in fact the effect even grows (because of the weekly data, we drop daily and holiday dummies). The adjusted R-square reaches 50% and all variables are significant with the exception of year 2011. For the weekly data, the merit order effect of other renewable sources is found to be - 2.5% with the inverse merit order of solar remaining + 0.7% (for 10% increase in production). Results are reported in Table 4.10.

The analysis was performed on hourly data, as well as on daily and weekly averages. For hourly data the solar MOE is close to zero but still non-negative, moreover, is not statistically significant (Table 4.8). For daily and weekly data solar MOE is statistically significant, however, still non-negative. The final results relate to weekly data.

Given that our results, at least at the first sight, contradict the MOE theory, following discussion presents the reasons why Czech solar MOE could be non-negative.

## 4.7 Discussion

The difference between solar and other sources and non-negative solar MOE is not as odd as it may seem. The Czech Republic is not a sunny country, according to the Czech Hydrometeorological Institute in August 2016 (the sunniest month of that year) Prague had 244 hours of sunshine, which gives on average less than 8 hours per day, and it had only 53 hours of sunshine in January 2016. As a consequence during an average day there are only about 5 hours with the solar production influencing the market (CHMI 2016).

If solar sources shift the supply curve only for few hours, the overall effect in a day does not result in a permanent MOE. The opposite is true for other renewable sources that supply the system continuously and thus they have the ability to shift the supply curve more often and cause the MOE. This is in agreement with Clò *et al.* (2015) who finds different monetary savings of solar MOE and wind MOE (the former does not compensate for its incentives costs, the latter does).

Photovoltaic production is aligned with peak hours but given that solar plants generate only 3% of the country's gross consumption, see Table 4.5, solar alone (due to few sunshine hours) may not be enough to push the marginal plant out of the market (i.e. cause price drop). The marginal (type of) plant may produce less because it is dispatchable but will stay in the market thus, the price would also remain. Better said, Czech solar alone could push the marginal plant out of the market, had it been working at its (close to) full capacity. But weather conditions in the Czech Republic do not allow the solar plants to reach reasonable efficiency ratio (defined as production/installed capacity), see Table 4.2. Another way to view this result is that the additional solar capacity was not able to offset the negative (i.e. price increasing) effect of additional volatility caused by unpredictable production of photovoltaic plants.

Czech Republic is net electricity exporter (see Table 4.1) so the reserve margin is significant. Given that the Czech electricity market is generally used to excess capacity, see Table 4.2, extra excess capacity in terms of RES does not mean an important change of market conditions. In case of electricity the downward pressure of growing supply on price is weakened by its non-storability, necessity for instantaneous supply-demand matching and, in case of solar, also by limited production hours depending on sunshine. Should the Czech electricity production cover inland consumption needs only (theoretical case of no export), it is very probable that the electricity spot market price

would be lower as a consequence of increased supply.

We would like to highlight that our results are still in accordance with fundamental economic principles in that the market as a whole behaves as expected. Solar electricity is just one part of the market where we do not observe a price increase in reaction to solar supply growth (solar non-negative MOE). Given moderate sunshine intensity, the solar plants should have never consumed 60% (see Figure 4.2) of the Czech subsidies devoted to RES promotion. This suggests that the Czech application of the solar support scheme was flawed.

Despite market liberalization the market share of the largest generators in the EU countries did not change much (valid also for the Czech Republic), see Moreno *et al.* (2012) who also conclude that a deployment of RES caused a small price increase for households. Moreover, this study supports our belief that country's fixed effect matters which is part of an explanation of why Czech situation differs from other results documented in the MOE literature. (Welisch *et al.* 2016) also confirm that the effect differs across countries. As mentioned above, one of the key differences of the Czech market is its export share and number of solar plants in unfriendly weather conditions.

Our results may have important economic policy implications. If we care about being cost effective, then all renewables cannot be treated equally. As we have shown, only other (mainly continuously working) RES cause the MOE in the Czech Republic and thus bring some savings. Given that 60% of Czech RES subsidies goes to solar power plants, then we may consider the current situation suboptimal.

Let us return to the initial intuition from the Methodology section (Equation 4.1). How much would have wholesale electricity cost, had there been no RES? Our results imply that a 10% increase in production of renewable sources without solar results in a 2.5% decrease in electricity price. In 2014, the share of renewables without solar was approximately 11%. If we estimate this share to be 10%, then we can apply our results to find the electricity wholesale price without RES support. No RES means 0%, the RES support till today caused 10% increase of renewables without solar and we know that a 10% increase in production of renewables without solar saves 2.5%. Thus, thanks to RES without solar electricity, wholesale price today is by 2.5% lower than it would be otherwise.

Let's consider the 2013 (rough) figures, the price of an average MWh was 30 euro, then the savings are 75 cents for every MWh. Given the total annual

production of 87 000 GWh, overall savings per year are about 65 million euro. Compared to the subsidies that amount to 2 billion euro, the RES support is shown to be a political decision.

## 4.8 Conclusions and Policy Implications

This paper assesses the impact of renewable energy in general and photovoltaic power plants in particular on the electricity supply curve, verifying the presence of merit order effect (MOE) in the Czech market. We estimate the MOE as elasticity of electricity spot price with respect to the change in supply of electricity from the renewable sources. We quantify the MOE based on hourly, daily and weekly data covering the time span of six years from 2010 to 2015.

Our model builds on the instrumental variable method, adjusting for autocorrelation in the time series. The estimated MOE is of the expected negative size but unexpectedly we conclude that it is not a global effect, in the sense that not every renewable source of energy contributes to the MOE. Due to the significant position of solar power in the Czech Republic, we have worked with two groups of renewables – solar, and other renewable sources excluding solar.

The analysis was performed on hourly data, as well as on daily and weekly averages. For hourly data the solar MOE is close to zero but still non-negative, moreover, is not statistically significant (Table 4.8). For daily and weekly data solar MOE is statistically significant, however, still non-negative. The final results relate to weekly data.

The estimated merit order effect of solar renewable sources is non-negative, creating double costs for end consumers – surcharge/subsidies and wholesale price non-decrease. Our results confirm the negative MOE for the remaining renewable sources, denoted as other RES – a 10% increase in production of other RES results in a 2.5% electricity price decrease. As a consequence, we can respond to the fundamental question – how much would electricity cost without RES? The share of RES causing MOE is approximately 10%, thus wholesale electricity costs about 2.5% less due to MOE.

Our results do not support the preferential treatment solar enjoyed in the Czech Republic. If we care about being cost effective, then the dominance of solar plants is not recommended as we have shown that the solar RES do not contribute to the MOE. Other mainly continuously working RES cause the MOE and thus bring some savings. Given that 60% of the Czech RES subsidies go to the solar power plants, we may consider the current situation subopti-

mal. Czech renewables, driven by the public support scheme, are the case of incorrectly implemented policy that should be avoided. We believe it is worth stressing as it is a policy mistake in the first place and it gives a valuable policy lesson.

Compared to the results of other countries, Czech absolute value of the MOE seems lower. This is driven by the dominance of solar plants which is not based on geographic conditions. Most likely the mix of renewable sources elsewhere reflects the natural environment better so that each RES can contribute to the MOE. For example in Germany, wind is the prevailing RES, it influences price also during the night which drives down the average price and the absolute value of the MOE up. In any case, lower wholesale price on the spot market does not directly affect consumer price, as the electricity contracts are long term and Czech wholesale price represents only 45% of the final consumer price. The remaining part is regulated and RES account for 15% of the final price (for the composition of Czech consumer price in 2015, see ERU (2014)).

MOE of solar power plants in the Czech Republic is found to be non-negative which points towards an inappropriate Czech solar policy. Results of our analysis reflect improper RES support implementation. Given Czech solar evolution we could have barely obtained textbook RES implementation results leading to lower prices. Our paper shows that Czech MOE savings do not outweigh the RES support costs. Their beneficial influence is minimal and it is outweighed by the negative impact in the form of costs of RES subsidies. Investment in other technologies for energy production suffers too (Winkler *et al.* 2016), as allegedly “free” green energy is difficult to compete with. The most important effect of the Czech RES support was not the shift of the supply curve, but the structural change of the market and 28 000 (OTE 2015b) new solar plants in the Czech Republic.

## Acknowledgments

The authors acknowledge support from the Czech Science Foundation grants number 15-00036S and 16-00027S. This project has received funding from the European Union’s Horizon 2020 Research and Innovation Staff Exchange programme under the Marie Skłodowska-Curie grant agreement No 681228. Karel Janda acknowledges research support provided during his long-term visits at Australian National University and McGill University. The views expressed in the paper are those of the authors and not necessarily those of our institutions.



# Bibliography

- ACT (2005): “Act on Promotion of Electricity Produced from Renewable Energy Sources No.180/2005 Coll.”
- ACT (2012): “Act on Supported Energy Sources and amendments to certain laws No.165/2012 Coll.”
- AL-GUDHEA, S., T. KENC, & S. DIBOGLU (2007): “Do retail gasoline prices rise more readily than they fall? a threshold cointegration approach.” *Journal of Economics and Business* **59(6)**: pp. 560–574.
- ALESSIO, E., A. CARBONE, G. CASTELLI, & V. FRAPPIETRO (2002): “Second-order moving average and scaling of stochastic time series.” *European Physical Journal B* **27**: pp. 197–200.
- ALOGOSKOUFIS, G. & R. SMITH (1991): “On error correction models: specification, interpretation, estimation.” *Journal of Economic Surveys* **5(1)**: pp. 97–128.
- ALVAREZ-RAMIREZ, J., M. CISNEROS, C. IBARRA-VALDEZ, & A. SORIANO (2002): “Multifractal Hurst analysis of crude oil prices.” *Physica A: Statistical Mechanics and its Applications* **313**: pp. 651–670.
- ALVAREZ-RAMIREZ, J. & R. ESCARELA-PEREZ (2010): “Time-dependent correlations in electricity markets.” *Energy Economics* **32**: pp. 269–277.
- ASBURY, C. (1975): “Weather load model for electric demand and energy forecasting.” *Power Apparatus and Systems, IEEE Transactions on* **94(4)**: pp. 1111–1116.
- BACHMEIER, L. J. & J. M. GRIFFIN (2003): “New evidence on asymmetric gasoline price responses.” *Review of Economics and Statistics* **85(3)**: pp. 772–776.

- BACON, R. W. (1991): “Rockets and feathers: The asymmetric speed of adjustment of UK retail gasoline prices to cost changes.” *Energy Economics* **13(3)**: pp. 211–218.
- BALKE, N. S., S. P. BROWN, & M. YÜCEL (1998): “Crude oil and gasoline prices: An asymmetric relationship?” *Economic and Financial Policy Review* **1**: pp. 2–11.
- BALMACEDA, F. & P. SORUCO (2008): “Asymmetric dynamic pricing in a local gasoline retail market.” *The Journal of Industrial Economics* **56(3)**: pp. 629–653.
- BARLOW, M. T. (2002): “A diffusion model for electricity prices.” *Mathematical Finance* **12(4)**: pp. 287–298.
- BARUNIK, J. & L. KRISTOUFEK (2010): “On Hurst exponent estimation under heavy-tailed distributions.” *Physica Physica A: Statistical Mechanics and its Applications* **389(18)**: pp. 3844–3855.
- BEJBL, J., J. BEMŠ, T. KRÁLÍK, O. STARÝ, & J. VASTL (2014): “New approach to brown coal pricing using internal rate of return methodology.” *Applied Energy* **133**: pp. 289–297.
- BERAN, J. (1994): *Statistics for Long-Memory Processes*, volume 61 of *Monographs on Statistics and Applied Probability*. New York: Chapman and Hall.
- BETTENDORF, L., S. A. VAN DER GEEST, & M. VARKEVISSER (2003): “Price asymmetry in the dutch retail gasoline market.” *Energy Economics* **25(6)**: pp. 669–689.
- BORENSTEIN, S., J. BUSHNELL, & S. STOFT (1997a): “The competitive effects of transmission capacity in a deregulated electricity industry.” *Technical report*, National Bureau of Economic Research.
- BORENSTEIN, S., A. C. CAMERON, & R. GILBERT (1997b): “Do gasoline prices respond asymmetrically to crude oil price changes?” *The Quarterly Journal of Economics* **112(1)**: pp. 305–339.
- BORENSTEIN, S. & A. SHEPARD (2002): “Sticky prices, inventories, and market power in wholesale gasoline markets.” *RAND Journal of Economics* **33**: pp. 116–139.

- BROWN, S. P. & M. K. YÜCEL (2000): “Gasoline and crude oil prices: why the asymmetry?” *Economic and Financial Policy Review* **3(Q3)**: pp. 23–29.
- CEPS (2015a): “Czech electricity transmission system: Generation Data.” <http://www.ceps.cz/ENG/Data/Vsechna-data/Pages/default.aspx>.
- CEPS (2015b): “Czech Electricity Transmission System: Preparation of Annual Operation 2015.” [http://www.ceps.cz/CZE/Cinnosti/Dispecerske\\_rizeni/Priprava\\_provozu/Stranky/default.aspx](http://www.ceps.cz/CZE/Cinnosti/Dispecerske_rizeni/Priprava_provozu/Stranky/default.aspx).
- CHEN, L.-H., M. FINNEY, & K. S. LAI (2005): “A threshold cointegration analysis of asymmetric price transmission from crude oil to gasoline prices.” *Economics Letters* **89(2)**: pp. 233–239.
- CHMI (2016): “Czech Hydrometeorological Institute: Hours of Sunshine Statistics.” <http://portal.chmi.cz/historicka-data/pocasi/mesicni-data#>.
- CIARRETA, A. & A. ZARRAGA (2010): “Economic growth–electricity consumption causality in 12 european countries: A dynamic panel data approach.” *Energy Policy* **38(7)**: pp. 3790–3796.
- CLÒ, S., A. CATALDI, & P. ZOPPOLI (2015): “The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices.” *Energy Policy* **77**: pp. 79–88.
- CONT, R. (2001): “Empirical properties of asset returns: stylized facts and statistical issues.” *Quantitative Finance* **1(2)**: pp. 223 – 236.
- CRAMTON, P., A. OCKENFELS, S. STOFT *et al.* (2013): “Capacity market fundamentals.” *Economics of Energy & Environmental Policy* **2(2)**: pp. 27–46.
- CTK (2014): “Czech News Agency: News archive - infobank.” <https://ib.ctk.cz/>.
- DELTAS, G. (2008): “Retail gasoline price dynamics and local market power.” *The Journal of Industrial Economics* **56(3)**: pp. 613–628.
- DI MATTEO, T. (2007): “Multi-scaling in finance.” *Quantitative Finance* **7(1)**: pp. 21–36.

- DI MATTEO, T., T. ASTE, & M. DACOROGNA (2003): “Scaling behaviors in differently developed markets.” *Physica A: Statistical Mechanics and its Applications* **324**: pp. 183–188.
- DICKEY, D. & W. FULLER (1979): “Distribution of the estimators for autoregressive time series with a unit root.” *Journal of the American Statistical Association* **74(366)**: pp. 427–431.
- DILLIG, M., M. JUNG, & J. KARL (2016): “The impact of renewables on electricity prices in Germany – an estimation based on historic spot prices in the years 2011–2013.” *Renewable and Sustainable Energy Reviews* **57**: pp. 7–15.
- DOUGLAS, C. C. (2010): “Do gasoline prices exhibit asymmetry? Not usually!” *Energy Economics* **32(4)**: pp. 918–925.
- DUFFY-DENO, K. T. (1996): “Retail price asymmetries in local gasoline markets.” *Energy Economics* **18(1)**: pp. 81–92.
- DURBIN, J. & G. WATSON (1971): “Testing for serial correlation in least squares regression.” *Biometrika* **58(1)**: pp. 1–19.
- ECKERT, A. (2002): “Retail price cycles and response asymmetry.” *Canadian Journal of Economics/Revue canadienne d'économie* **35(1)**: pp. 52–77.
- EFRON, B. (1987): “Better bootstrap confidence intervals.” *Journal of the American Statistical Association* **82**: pp. 171–185.
- EFRON, B. & C. STEIN (1981): “The jackknife estimate of variance.” *The Annals of Statistics* **9**: pp. 586–596.
- ENGLE, R. & C. GRANGER (1987): “Co-integration and error correction: Representation, estimation and testing.” *Econometrica* **55**: pp. E251–276.
- ERU (2013): “Price Decision of the Energy Regulatory Office no. 4/2013 dated 27.11.2013.”
- ERU (2014): “Energy Regulatory Office: Press release 26.11.2014.” <http://www.eru.cz/-/informace-o-regulovanych-cenach-energie-na-rok-2015>.
- ERU (2015): “Energy Regulatory Office: Annual report on the operation of the energy system in the Czech Republic in 2015.” <http://www.eru.cz/en/>.

- ERZGRABER, H., F. STROZZI, J.-M. ZALDIVAR, H. TOUCHETTE, E. GUTIERREZ, & D. ARROWSMITH (2008): "Time series analysis and long range correlations of Nordic spot electricity market data." *Physica A: Statistical Mechanics and its Applications* **387**: pp. 6567–6574.
- EU (2014): "The European Union 2030 Energy Strategy." <https://ec.europa.eu/energy/en/topics/energy-strategy/2030-energy-strategy>.
- GALEOTTI, M., A. LANZA, & M. MANERA (2003): "Rockets and feathers revisited: an international comparison on European gasoline markets." *Energy Economics* **25**: pp. 175–190.
- GELABERT, L., X. LABANDEIRA, & P. LINARES (2011): "An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices." *Energy Economics* **33**: pp. S59–S65.
- GEMAN, H. (2005): "Energy commodity prices: Is mean-reversion dead?" *The Journal of Alternative Investments* **8(2)**: pp. 31–45.
- GEMAN, H. & A. RONCORONI (2006): "Understanding the fine structure of electricity prices." *The Journal of Business* **79(3)**: pp. 1225–1261.
- GEWEKE, J. & S. PORTER-HUDAK (1983): "The estimation and application of long memory time series models." *Journal of Time Series Analysis* **4(4)**: pp. 221–238.
- GIRAITIS, L., P. KOKOSZKA, R. LEIPUS, & G. TEYSSIERE (2003): "Rescaled variance and related tests for long memory in volatility and levels." *Journal of Econometrics* **112**: pp. 265–294.
- GODBY, R., A. M. LINTNER, T. STENGOS, & B. WANDSCHNEIDER (2000): "Testing for asymmetric pricing in the Canadian retail gasoline markets." *Energy Economics* **22(3)**: pp. 349–368.
- GRANT, T. & M. J. LEBO (2016): "Error correction methods with political time series." *Political Analysis* **24(1)**: pp. 3–30.
- GRASSO, M. & M. MANERA (2007): "Asymmetric error correction models for the oil-gasoline price relationship." *Energy Policy* **35(1)**: pp. 156–177.

- GRECH, D. & Z. MAZUR (2005): “Statistical properties of old and new techniques in detrended analysis of time series.” *Acta Physica Polonica B* **36**: pp. 2403–2413.
- HALL, P. & S. WILSON (1991): “Two guidelines for bootstrap hypothesis testing.” *Biometrics* **47**: pp. 757–762.
- HAUGOM, E., S. WESTGAARD, P. B. SOLIBAKKE, & G. LIEN (2011): “Realized volatility and the influence of market measures on predictability: Analysis of Nord Pool forward electricity prices.” *Energy Economics* **33**: pp. 1206–1215.
- HAVLÍČKOVÁ, K., J. WEGER, & J. KNÁPEK (2011): “Modelling of biomass prices for bio-energy market in the Czech Republic.” *Simulation Modelling Practice and Theory* **19(9)**: pp. 1946–1956.
- HAVRANEK, T., Z. IRSOVA, K. JANDA, & D. ZILBERMAN (2015): “Selective reporting and the social cost of carbon.” *Energy Economics* **51**: pp. 394–406.
- HONARVAR, A. (2009): “Asymmetry in retail gasoline and crude oil price movements in the United States: An application of hidden cointegration techniques.” *Energy Economics* **31(3)**: pp. 395–402.
- HU, K., P. IVANOV, Z. CHEN, P. CARPENA, & H. STANLEY (2001): “Effect of trends on detrended fluctuation analysis.” *Physical Review E* **64**: p. 011114.
- HURST, H. (1951): “Long term storage capacity of reservoirs.” *Transactions of the American Society of Engineers* **116**: pp. 770–799.
- JANCZURA, J., S. TRUECK, R. WERON, & R. C. WOLFF (2013): “Identifying spikes and seasonal components in electricity spot price data: A guide to robust modeling.” *Energy Economics* **38**: pp. 96–110.
- JANDA, K., S. KRŠKA, & J. PRUSA (2014): “Czech Photovoltaic Energy: Model Estimation of The Costs of its Support.” *Politická ekonomie* **62(3)**: pp. 323–346.
- JANDA, K., J. MALEK, & L. RECKA (2016): “Influence of renewable energy sources on transmission networks in Central Europe.” *Working Paper 68/2016*, CAMA, Australian National University, Canberra, Australia.
- JANDA, K. & L. TUMA (2016): “Impact of solar production on Czech electricity grid system imbalance.” *Working Paper 74883*, MPRA, University Library of Munich, Germany.

- JARQUE, C. & A. BERA (1980): “Efficient tests for normality, homoskedasticity and serial independence of regression residuals.” *Economics Letters* **6(3)**: pp. 255–259.
- JARQUE, C. & A. BERA (1981): “Efficient tests for normality, homoskedasticity and serial independence of regression residuals: Monte Carlo evidence.” *Economics Letters* **7(4)**: pp. 313–318.
- JOHNSON, R. N. (2002): “Search costs, lags and prices at the pump.” *Review of Industrial Organization* **20(1)**: pp. 33–50.
- KANTELHARDT, J. (2009): *Encyclopedia of Complexity and Systems Science*, chapter Fractal and Multifractal Time Series. Springer.
- KANTELHARDT, J., S. ZSCHIEGNER, E. KOSCIELNY-BUNDE, A. BUNDE, S. HAVLIN, & E. STANLEY (2002): “Multifractal Detrended Fluctuation Analysis of Nonstationary Time Series.” *Physica A: Statistical Mechanics and its Applications* **316(1-4)**: pp. 87–114.
- KARASEK, J. & J. PAVLICA (2016): “Green Investment Scheme: Experience and results in the Czech Republic.” *Energy Policy* **90**: pp. 121–130.
- KARRENBROCK, J. D. (1991): “The behavior of retail gasoline prices: symmetric or not?” *Federal Reserve Bank of St. Louis Review* **73(July/August 1991)**: pp. 19–29.
- KAUFMANN, R. K. & C. LASKOWSKI (2005): “Causes for an asymmetric relation between the price of crude oil and refined petroleum products.” *Energy Policy* **33(12)**: pp. 1587–1596.
- KELES, D., M. GENOESE, D. MÖST, S. ORTLIEB, & W. FICHTNER (2013): “A combined modeling approach for wind power feed-in and electricity spot prices.” *Energy Policy* **59**: pp. 213–225.
- KELLER, C., V. VISSCHERS, & M. SIEGRIST (2012): “Affective imagery and acceptance of replacing nuclear power plants.” *Risk Analysis* **32(3)**: pp. 464–477.
- KNITTEL, C. R. & M. R. ROBERTS (2005): “An empirical examination of restructured electricity prices.” *Energy Economics* **27(5)**: pp. 791–817.

- KOOPMAN, S. J., M. OOMS, & M. A. CARNERO (2007): “Periodic seasonal reg-arfima-garch models for daily electricity spot prices.” *Journal of the American Statistical Association* **102(477)**: pp. 16–27.
- KRISTOUFEK, L. (2010): “Rescaled range analysis and detrended fluctuation analysis: Finite sample properties and confidence intervals.” *AUCO Czech Economic Review* **4**: pp. 236–250.
- KRISTOUFEK, L. (2013): “Mixed-correlated arfima processes for power-law cross-correlations.” *Physica A* **392**: pp. 6484–6493.
- KRIŠTOUFEK, L. & P. LUŇÁČKOVÁ (2013): “Long-term memory in electricity prices: Czech market evidence.” *Finance a úvěr – Czech Journal of Economics and Finance* **63(5)**: pp. 407–424.
- KU LEUVEN ENERGY INSTITUTE (2015): “The current electricity market design in Europe.” <http://set.kuleuven.be/ei/factsheets>.
- KÜNSCH, H. (1987): “Statistical aspects of self-similar processes.” *Proceedings of the First World Congress of the Bernoulli Society* **1**: pp. 67–74.
- KUNSCH, H. (1989): “The jackknife and the bootstrap for general stationary observations.” *The Annals of Statistics* **17**: pp. 1217–1241.
- KWIATKOWSKI, D., P. PHILLIPS, P. SCHMIDT, & Y. SHIN (1992): “Testing the null of stationarity against alternative of a unit root: How sure are we that the economic time series have a unit root?” *Journal of Econometrics* **54**: pp. 159–178.
- LAVANCIER, F., A. PHILIPPE, & D. SURGAILIS (2010): “A two-sample test for comparison of long memory parameters.” *Journal of Multivariate Analysis* **101**: pp. 2118–2136.
- LEE, C.-C. (2005): “Energy consumption and gdp in developing countries: a cointegrated panel analysis.” *Energy Economics* **27(3)**: pp. 415–427.
- LEWIS, M. S. (2011): “Asymmetric price adjustment and consumer search: An examination of the retail gasoline market.” *Journal of Economics & Management Strategy* **20(2)**: pp. 409–449.
- LIU, M.-H., D. MARGARITIS, & A. TOURANI-RAD (2010): “Is there an asymmetry in the response of diesel and petrol prices to crude oil price changes? evidence from new zealand.” *Energy Economics* **32(4)**: pp. 926–932.



- LUCIA, J. J. & E. S. SCHWARTZ (2002): “Electricity prices and power derivatives: Evidence from the Nordic Power Exchange.” *Review of Derivatives Research* **5(1)**: pp. 5–50.
- MALO, P. (2009): “Modeling electricity spot and futures price dependence: A multifrequency approach.” *Physica A* **388**: pp. 4763–4779.
- MANDELBROT, B. (1971): “Analysis of long-run dependence in economics: The R/S techniques.” *Econometrica* **39**: pp. 68–69.
- MANDELBROT, B. (1972): “Statistical methodology for non-periodic cycles: from covariance to R/S analysis.” *Annals of Economic and Social Measurement* **1(3)**: pp. 259–290.
- MANDELBROT, B. & J. VAN NESS (1968): “Fractional brownian motions, fractional noises and applications.” *SIAM Review* **10(422)**: pp. 422–437.
- MANDELBROT, B. & J. WALLIS (1968): “Noah, Joseph and Operational Hydrology.” *Water Resources Research* **4(5)**: pp. 909–918.
- MCCONNELL, D., P. HEARPS, D. EALES, M. SANDIFORD, R. DUNN, M. WRIGHT, & L. BATEMAN (2013): “Retrospective modeling of the merit-order effect on wholesale electricity prices from distributed photovoltaic generation in the Australian National Electricity Market.” *Energy Policy* **58**: pp. 17–27.
- MILSTEIN, I. & A. TISHLER (2011): “Intermittently renewable energy, optimal capacity mix and prices in a deregulated electricity market.” *Energy Policy* **39(7)**: pp. 3922–3927.
- MORENO, B., A. J. LÓPEZ, & M. T. GARCÍA-ÁLVAREZ (2012): “The electricity prices in the European Union. The role of renewable energies and regulatory electric market reforms.” *Energy* **48(1)**: pp. 307–313.
- MPO (2015): “Ministry of Industry and Trade: State Budget.” <http://www.mpo.cz/cz/rozcestnik/ministerstvo/o-ministerstvu/rozpocet/>.
- MULDER, M. & B. SCHOLTENS (2013): “The impact of renewable energy on electricity prices in the Netherlands.” *Renewable Energy* **57**: pp. 94–100.
- MUNKSGAARD, J. & P. E. MORTHORST (2008): “Wind power in the Danish liberalised power market: Policy measures, price impact and investor incentives.” *Energy Policy* **36(10)**: pp. 3940–3947.

- NAGY ELTONY, M. (1998): “The asymmetry of gasoline prices: fresh evidence from an error correction model for uk and usa.” *International journal of energy research* **22(3)**: pp. 271–276.
- NELSON, T., P. SIMSHAUSER, & J. NELSON (2012): “Queensland solar feed-in tariffs and the merit-order effect: Economic benefit, or regressive taxation and wealth transfers?” *Economic Analysis and Policy* **42(3)**: pp. 277–301.
- NICOLOSI, M. & M. FÜRSCH (2009): “The impact of an increasing share of RES-E on the conventional power market - the example of Germany.” *Zeitschrift für Energiewirtschaft* **33(3)**: pp. 246–254.
- NOROZZADEH, P., W. DULLAERT, & B. RAHMANI (2007): “Anti-correlation and multifractal features of Spain electricity spot market.” *Physica A: Statistical Mechanics and its Applications* **380**: pp. 333–342.
- NREL (2015): “U.S. National Renewable Energy Laboratory.” [http://www.nrel.gov/csp/solarpaces/by\\_country.cfm](http://www.nrel.gov/csp/solarpaces/by_country.cfm).
- OLADUNJOYE, O. (2008): “Market structure and price adjustment in the us wholesale gasoline markets.” *Energy Economics* **30(3)**: pp. 937–961.
- OTE (2013): “Czech electricity and gas market operator: Annual Report 2013.”
- OTE (2014): “Czech electricity and gas market operator: Press Release 19.11.2014.” <http://www.ote-cr.cz/o-spolecnosti/files-novinky/pcr-pr-4m-mc-launch.pdf>.
- OTE (2015a): “Czech electricity and gas market operator: Price Data Statistics.” <http://www.ote-cr.cz/statistika/rocnizprava>.
- OTE (2015b): “Czech electricity and gas market operator: Product sheet 2015.” [http://www.ote-cr.cz/about-ote/main-reading?set\\_language=en](http://www.ote-cr.cz/about-ote/main-reading?set_language=en).
- PANAGIOTIDIS, T. & E. RUTLEDGE (2007): “Oil and gas markets in the uk: Evidence from a cointegrating approach.” *Energy economics* **29(2)**: pp. 329–347.
- PARK, H., J. W. MJELDE, & D. A. BESSLER (2006): “Price dynamics among U.S. electricity spot markets.” *Energy Economics* **28**: pp. 81–101.

- PELTZMAN, S. (2000): "Prices rise faster than they fall." *Journal of Political Economy* **108(3)**: pp. 466–502.
- PENG, C., S. BULDYREV, A. GOLDBERGER, S. HAVLIN, M. SIMONS, & H. STANLEY (1993): "Finite-size effects on long-range correlations: Implications for analyzing DNA sequences." *Physical Review E* **47(5)**: pp. 3730–3733.
- PENG, C., S. BULDYREV, S. HAVLIN, M. SIMONS, H. STANLEY, & A. GOLDBERGER (1994): "Mosaic organization of DNA nucleotides." *Physical Review E* **49(2)**: pp. 1685–1689.
- PHILLIPS, P. C. B. & K. SHIMOTSU (2004): "Local whittle estimation in non-stationary and unit root cases." *The Annals of Statistics* **32(2)**: pp. 659–692.
- PRAIS, S. & C. WINSTEN (1954): "Trend estimation and serial correlation." *Cowles Foundation Discussion Paper* **383**.
- PRUSA, J., A. KLIMESOVA, & K. JANDA (2013): "Consumer loss in Czech photovoltaic power plants in 2010–2011." *Energy Policy* **63**: pp. 747–755.
- RADCHENKO, S. (2005): "Oil price volatility and the asymmetric response of gasoline prices to oil price increases and decreases." *Energy economics* **27(5)**: pp. 708–730.
- RECKA, L. & M. SCASNY (2016): "Impacts of carbon pricing, brown coal availability and gas cost on Czech energy system up to 2050." *Energy* pp. 19–33.
- REILLY, B. & R. WITT (1998): "Petrol price asymmetries revisited." *Energy Economics* **20(3)**: pp. 297–308.
- REISEN, V. (1994): "Estimation of the fractional difference parameter in the ARFIMA(p,q,d) model using the smoothed periodogram." *Journal of Time Series Analysis* **15**: pp. 335–350.
- REISEN, V., B. ABRAHAM, & E. TOSCANO (2000): "Parametric and semi-parametric estimations of stationary univariate ARFIMA models." *Brazilian Journal of Probability and Statistics* **14**: pp. 185–206.
- ROBINSON, P. (1994): "Semiparametric analysis of long-memory time series." *Annals of Statistics* **22**: pp. 515–539.

- ROBINSON, P. (1995a): “Gaussian semiparametric estimation of long range dependence.” *The Annals of Statistics* **23(5)**: pp. 1630–1661.
- ROBINSON, P. (1995b): “Gaussian semiparametric estimation of long range dependence.” *The Annals of Statistics* **23(5)**: pp. 1630–1661.
- RYPDAL, M. & O. LOVSLETEN (2013): “Modeling electricity spot prices using mean-reverting multifractal processes.” *Physica A: Statistical Mechanics and its Applications* **392**: pp. 194–207.
- SAMORODNITSKY, G. (2006): “Long range dependence.” *Foundation and Trends<sup>®</sup> in Stochastic Systems* **1(3)**: pp. 163–257.
- SENSFUSS, F., M. RAGWITZ, & M. GENOESE (2008): “The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany.” *Energy Policy* **36(8)**: pp. 3086–3094.
- SHAPIRO, S. & M. WILK (1965): “An analysis of variance test for normality (complete samples).” *Biometrika* **52(3-4)**: pp. 591–611.
- SIMONSEN, I. (2003): “Measuring anti-correlations in the nordic electricity spot market by wavelets.” *Physica A: Statistical Mechanics and its Applications* **322**: pp. 597–606.
- SIMONSEN, I., R. WERON, & B. MO (2004): “Structure and stylized facts of a deregulated power market.” *MPRA Paper* **1443**: pp. 1–29.
- SIVEK, M., P. KAVINA, J. JIRÁSEK, & V. MALEČKOVÁ (2012a): “Czech Republic and indicative targets of the European Union for electricity generation from renewable sources.” *Energy Policy* **44**: pp. 469–475.
- SIVEK, M., P. KAVINA, J. JIRÁSEK, & V. MALEČKOVÁ (2012b): “Factors influencing the selection of the past and future strategies for electricity generation in the Czech Republic.” *Energy Policy* **48**: pp. 650–656.
- SMRČKA, L. (2011): “Photovoltaics in the Czech Republic: Example of a distorted market.” In “6th IASME/WSEAS International Conference on Energy and Environment,” pp. 378–383.
- SOVACOOOL, B. K. (2009): “The intermittency of wind, solar, and renewable electricity generators: Technical barrier or rhetorical excuse?” *Utilities Policy* **17(3)**: pp. 288–296.

- SOYTAS, U. & R. SARI (2003): “Energy consumption and gdp: causality relationship in g-7 countries and emerging markets.” *Energy economics* **25(1)**: pp. 33–37.
- SQUALLI, J. (2007): “Electricity consumption and economic growth: bounds and causality analyses of opec members.” *Energy Economics* **29(6)**: pp. 1192–1205.
- ŠŮRI, M., T. A. HULD, E. D. DUNLOP, & H. A. OSSENBRINK (2007): “Potential of solar electricity generation in the European Union member states and candidate countries.” *Solar energy* **81(10)**: pp. 1295–1305.
- TAPPATA, M. (2009): “Rockets and feathers: Understanding asymmetric pricing.” *The RAND Journal of Economics* **40(4)**: pp. 673–687.
- TAQQU, M., W. TEVEROSKY, & W. WILLINGER (1995): “Estimators for long-range dependence: an empirical study.” *Fractals* **3(4)**: pp. 785–798.
- TAQQU, M. & V. TEVEROVSKY (1996): “On Estimating the Intensity of Long-Range Dependence in Finite and Infinite Variance Time Series.” In “A Practical Guide To Heavy Tails: Statistical Techniques and Applications,” .
- THEILER, J., S. EUBANK, A. LONGTIN, B. GALDRIKIAN, & J. FARMER (1992): “Testing for nonlinearity in time series: the method of surrogate data.” *Physica D: Nonlinear Phenomena* **58**: pp. 77–94.
- TIMILSINA, G. R., L. KURDGELASHVILI, & P. A. NARBEL (2012): “Solar energy: Markets, economics and policies.” *Renewable and Sustainable Energy Reviews* **16(1)**: pp. 449–465.
- TORANI, K., G. RAUSSER, & D. ZILBERMAN (2016): “Innovation subsidies versus consumer subsidies: A real options analysis of solar energy.” *Energy Policy* **92**: pp. 255–269.
- TVETEN, Å. G., T. F. BOLKESJØ, T. MARTINSEN, & H. HVARNES (2013): “Solar feed-in tariffs and the merit order effect: A study of the German electricity market.” *Energy Policy* **61**: pp. 761–770.
- URITSKAYA, O. Y. & A. SERLETIS (2008): “Quantifying multiscale inefficiency in electricity markets.” *Energy Economics* **30**: pp. 3109–3117.

- VERLINDA, J. A. (2008): “Do rockets rise faster and feathers fall slower in an atmosphere of local market power? evidence from the retail gasoline market.” *The Journal of Industrial Economics* **56(3)**: pp. 581–612.
- VON BREMEN, L. (2010): “Large-scale variability of weather dependent renewable energy sources.” In “Management of Weather and Climate Risk in the Energy Industry,” pp. 189–206. Springer.
- VRBA, M., Z. ŠPAČEK, J. JEŽ, & J. PTÁČEK (2015): “Integration of electricity from renewable energy sources – The Czech story.” *Energy & Environment* **26(1-2)**: pp. 157–166.
- WELISCH, M., A. ORTNER, & G. RESCH (2016): “Assessment of RES technology market values and the merit-order effect – an econometric multi-country analysis.” *Energy & Environment* **27(1)**: pp. 105–121.
- WERON, R. (2002): *Empirical Science of Financial Fluctuations*, chapter Measuring long-range dependence in electricity prices, pp. 110–119. Springer-Verlag Tokyo.
- WERON, R. (2014): “Electricity price forecasting: A review of the state-of-the-art with a look into the future.” *International Journal of Forecasting* **30(4)**: pp. 1030–1081.
- WERON, R. & B. PRZYBYŁOWICZ (2000): “Hurst analysis of electricity price dynamics.” *Physica A: Statistical Mechanics and its Applications* **283(3)**: pp. 462–468.
- WINKLER, J., A. GAIO, B. PFLUGER, & M. RAGWITZ (2016): “Impact of renewables on electricity markets – Do support schemes matter?” *Energy Policy* **93**: pp. 157–167.
- WÜRZBURG, K., X. LABANDEIRA, & P. LINARES (2013): “Renewable generation and electricity prices: Taking stock and new evidence for Germany and Austria.” *Energy Economics* **40**: pp. S159–S171.
- ZACHMANN, G. (2008): “Electricity wholesale market prices in europe: Convergence?” *Energy Economics* **30(4)**: pp. 1659–1671.

# Appendix A

## Response to Opponents' Reports on Dissertation Thesis

Dear Opponents,

I would like to thank you, your recommendations have improved my dissertation considerably. Your reports were very helpful, I appreciate your comments, all of them are addressed below in detail. I have responded to all of your remarks and included majority of your suggestions into the final version of my dissertation.

### **Report of Adviser Prof. Karel Janda**

- *Comment 1: More detailed explanation of the major econometric result of the third article “The Merit Order Effect of Czech Photovoltaic Plants” and greater connection of the results to the literature.*

- *Response:* It is true that our results are quite surprising, however when put into the context of the Czech solar story, they make sense. The point is hidden in the low productivity of Czech solar power plants, not in the overall number of them. Actually, the results show that Czech solar production does not drive the marginal plant out of the market, the non-decrease of electricity wholesale price is a consequence. Unlike solar plants, the conventional sources are dispatchable and the entire Czech electricity production is considerable, so this scenario really is possible.

Further, literature confirms that the MOE is country specific. Paper by Clò *et al.* (2015) confirms that RES are not equal in their monetary

effect. Study by Mulder & Scholtens (2013) finds no impact of sunshine on electricity prices, the authors argue in a manner similar to ours, the shift of the supply curve is too small to affect the price level.

The explanation of the Czech non-negative solar MOE stands on three reasons - political, geographical and productivity. Czech geographical conditions do not favor solar power plants, actual production falls behind installed capacity and is marginal compared to overall production. Last but not least, political will to support RES allowed solar development that market would have never made possible (under the then conditions).

- *Comment 2 regards suitability of the electricity prices used for the analysis and the effect of market coupling.*
- *Response:* The spot (day ahead) electricity market price is widely accepted as reference price for electricity in both literature and trading. There is no “better” price series available, moreover the large share of export is covered by bilateral transactions (not traded in the day ahead market). The effect of market coupling is limited by the cross border infrastructure, besides also other European countries participate in market coupling. Current Multi-Regional Coupling covers countries from Finland to Spain.
- *Comment 3 concerns possible (theoretical) publication bias in favor of negative MOE.*
- *Response:* In order to accept or reject the hypothesis about publication bias, we would have to perform a different type of analysis possibly together with meta-analysis of the results, which goes beyond the scope of this dissertation.
- *Comment 4 regards the best instrument for the IV estimation in the MOE analysis.*
- *Response:* In the early stage of the analysis we considered also other instruments like weather, but we ruled out physical characteristic because of their low correlation with industrial demand and export (major consumers of the production from conventional sources). For details on the chosen instrument please see Chapter 4.5.



### Report of Opponent Prof. Dominik Möst

- *Comment 1 regards “long-term memory definition”.*
- *Response:* Long-term memory is defined in Chapter 2.3.1, even though it is called “long”, which we often (together with memory) associate with time, it is not defined in terms of units of time. Instead, it is defined by the specific decay of auto-correlation function, regardless the time dimension of the time series. There is specific vanishing pattern rather than time. The time ambiguity of long-term memory is now explained also in the thesis, please see General Introduction and extended Chapter 2.3.1.
- *Comment 2 concerns the innovative conclusion of the first paper “Long-term memory in electricity prices: Czech market evidence”.*
- *Response:* The first paper was a natural starting point, initial step for the second and third article. At the beginning, it was logical to look first at the electricity prices, analyze them and later on, equipped with this knowledge, use it in more complex analysis. That is also why, the second and third paper are published in journals ranked higher than the first one.
- *Comment 3 asks for the conclusion out of the identified price behavior, what can be learned from the analysis?*
- *Response:* Given that we have found no statistically significant asymmetry with regard to price adjustment, we suggest policy makers do not interfere. We did not identify any market failure, hence we believe there is no need for interventions. Our suggestion is now included also in the Chapter 3.6.
- *Comment 4: The sentence in the General Introduction “The second paper is devoted to...” was reformulated as suggested by the opponent.*
- *Comment 5 regards the not observed solar MOE for hourly and daily data.*
- *Response:* The analysis was performed on hourly data, as well as on daily and weekly averages. For hourly data the solar MOE is close to zero but still non-negative, moreover, is not statistically significant (Table 4.8). For daily and weekly data solar MOE is statistically significant, however, still non-negative. The final results relate to weekly data, which is now made more clear in the concluding Chapter 4.8.

Table A.1: Overview of the Contribution of Petra Lunackova

	Idea	Literature	Analysis and interpretation	Writing and final touch
Essay no.1 "Long memory... "	50%	80%	40%	50%
Essay no.2 "Rockets... "	50%	90%	40%	50%
Essay no.3 "MOE... "	80%	100%	90%	90%

- *Comment 6: We followed the suggestion of the opponent and the final conclusion of the third paper regarding green policy consequences is now less strong, admitting that the issue cannot be so simplified. Please see General Introduction.*
- *Comment 7: For the overview of the author's contribution please see Table A.1.*

**Report of Opponent Prof. Jaroslav Knápek**

- *Comment 1: As suggested by the opponent the list of abbreviations was added.*
- *Comment 2: As suggested by the opponent the General Introduction was extended - results of the thesis are presented in connection to current electricity markets and contribution of the thesis is discussed. Together with the contribution also the aim of the thesis is elaborated.*
- *Comment 3: Dissertations at the IES FSV UK often present formal (general) conclusion together with the (general) introduction. I have decided to follow this custom, thus open topics for the follow-up research are discussed at the end of the General Introduction chapter.*

### Report of Opponent Dr. Sherzod Tashpulatov

- *Comment 1: Minor comments for the dissertation abstract*
- *Response:* All comments are addressed in the thesis. Quotations marks and typos are corrected, second sentence is made clear and the description of the importance of gasoline-crude oil relationship for electricity markets is added. Abstract in Czech language is also added.
- *Comment 2: Minor comments for Introduction*
- *Response:* Introduction is renamed to “General Introduction”, the second sentence is rephrased and the fourth paragraph includes now also the description of the level of development of the Czech electricity market (compared to western EU countries).

- *Comment 3: Comments for Chapter 1*

- *Response:* Actually, both steps are done, first the time series is “de-meanned” and later on it is “detrended”.

As suggested “electricity consumption” was replaced by “demand for electricity” and the market coupling is mentioned.

The more general setting of the MF-DFA is presented in order to introduce the concept in general (some readers might find it useful).

The change in price (Table 2.1) is relative.

As a matter of fact, it is a disadvantage of the DFA, that its asymptotic properties are not defined. That is why we cannot discuss the power of statistical estimates and that is also the reason why we have included alternative estimators (like GPH), to support our interpretation of the DFA results.

- *Comment 4: Minor comments for Chapter 2*
- *Response:* The listed countries were chosen due to the data set restriction (the data set is tax adjusted). The difference mentioned is logarithmic (not log-arithmetic). The missing citation is now displayed.
- *Comment 5: Comments for Chapter 3*
- *Response:* Both figures were improved as suggested by the opponent.

- *Comment 6: Minor comments for Bibliography*
- *Response:* Bibliography was reviewed for missing issue numbers (where possible). Capitalization of ARFIMA and “Physica” were corrected.